ECEN721: Optical Interconnects Circuits and Systems
Spring 2024

Lecture 12: Laser Sources

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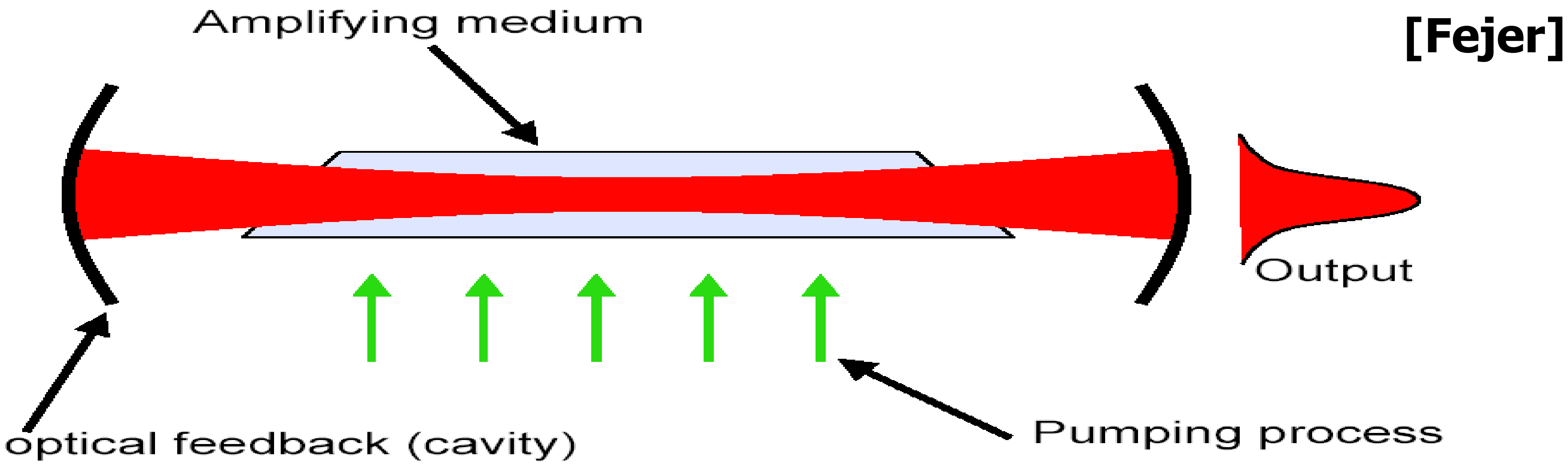
Announcements

- Project Preliminary Report (HW4) due Apr 16

- Reading
  - Sackinger Chapter 7

What is a Laser?

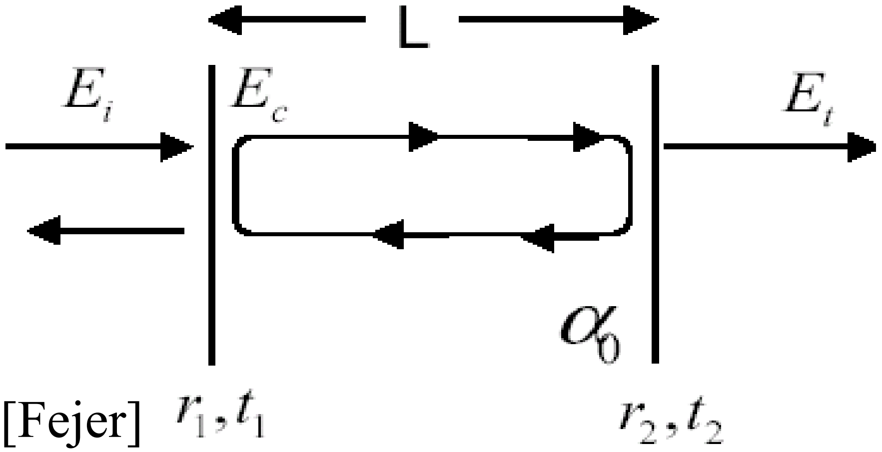


- **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation
- **L**ight **O**scillation by **S**timulated **E**mission of **R**adiation
- Lasers are optical oscillators that emit coherent light through the process of stimulated emission
- 3 Elements in all lasers
  - Amplifying Medium
  - Pumping Process
  - Optical Feedback (Cavity)

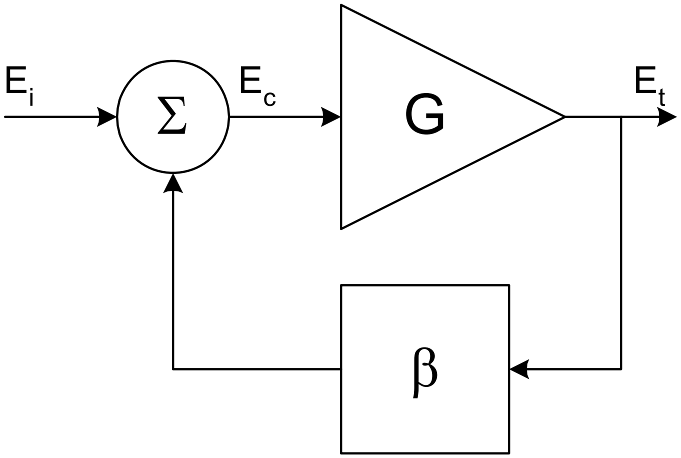
Agenda

- Fabry-Perot Lasers
- Distributed-Feedback (DFB) Lasers
- Hybrid Silicon Lasers
- Comb Lasers
- A 14 Gb/s Directly Modulated Hybrid Microring Laser Transmitter
- A Directly Modulated Quantum Dot Microring Laser Transmitter with Integrated CMOS Driver
- A 22Gb/s Directly Modulated Optical Injection-Locked Quantum-Dot Microring Laser Transmitter with Integrated CMOS Driver

Fabry-Perot Interferometer



[Fejer]



$$\frac{E_t}{E_i} = \frac{G}{1-\beta G}$$

- In order to "lase" or be an optical oscillator

$$\beta G = 1 \qquad \text{where} \qquad \begin{aligned} \beta &= r_1 r_2 \\ G &= e^{(g-\alpha)2L} e^{-ik2L} \end{aligned}$$

$r =$ mirror reflectivities (field)

$g =$ gain coefficient $\left(\frac{1}{\mathrm{m}}\right)$

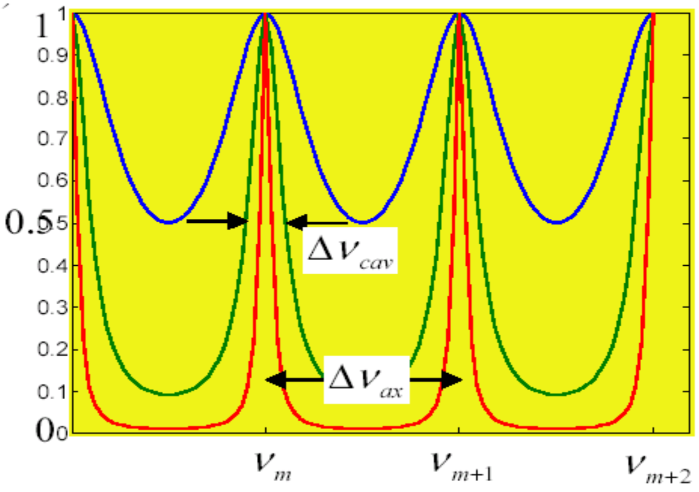
$\alpha =$ loss coefficient

$L =$ optical cavity length

$k = \frac{2\pi n}{\lambda}$ (field wavevector)

- Gain Condition: $\beta G = 1 \Rightarrow g = \alpha + \frac{1}{2L}\ln\left(\frac{1}{r_1 r_2}\right)$
- Round-trip gain must equal cavity losses & mirror transmission

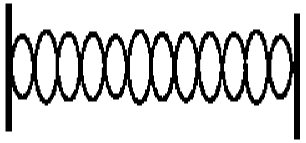
Fabry-Perot Interferometer (2)



[Fejer]

- Phase Condition: $e^{-ik2L} = 1 \Rightarrow k2L = m2\pi$

$$L = \frac{m\lambda}{2n} \Rightarrow$$



- Phase condition makes this an "optical bandpass filter" – wavelengths transmitted correspond to an integer number of λ/2 in a length L

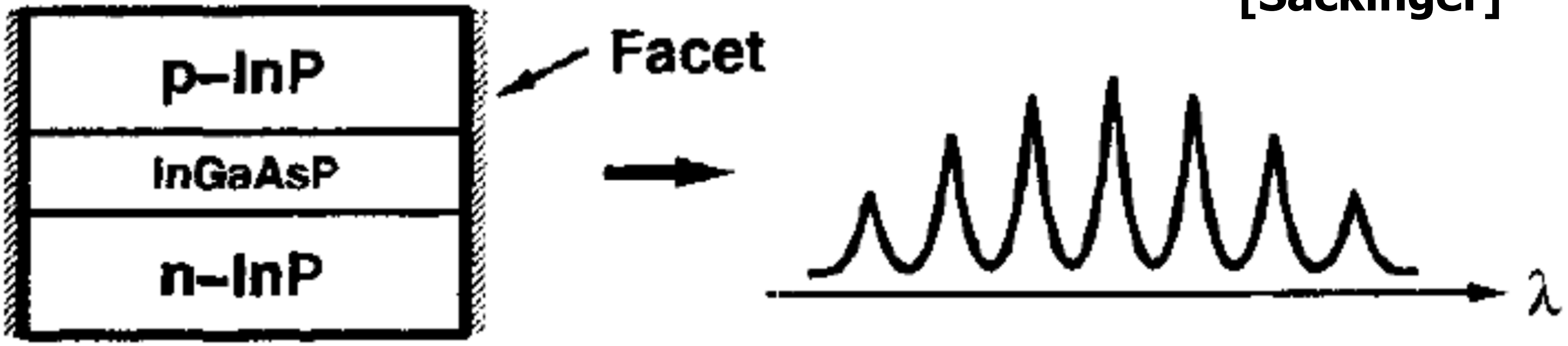
$$\text{Transmitted Wavelength}: \lambda = \frac{2Ln}{m} \qquad \text{Frequency}: f = m\left(\frac{c}{2Ln}\right)$$

- The transmitted wavelengths/frequencies are called the longitudinal modes of oscillation

$$\text{Mode Spacing}: \Delta\lambda = \frac{\lambda^2}{2Ln} \qquad \Delta\nu_{ax} = \frac{c}{2Ln}$$

Fabry-Perot Laser

[Sackinger]



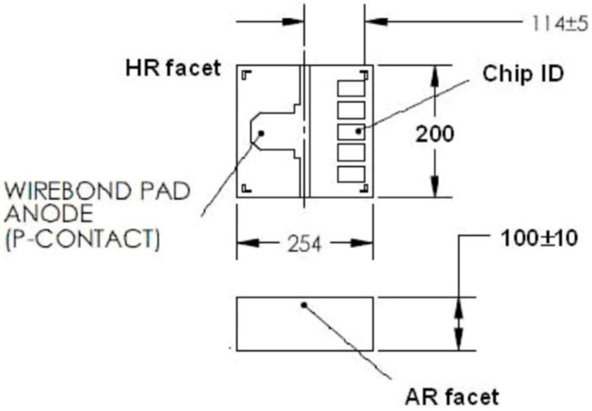
- Laser gain medium formed by a forward-biased p-n junction
- Carriers electrically "pump" the active region such that an incoming photon can stimulate electron-hole pair recombination to produce another identical photon
- Long cavity length (300μm) results in multiple-longitudinal modes and large spectral linewidths

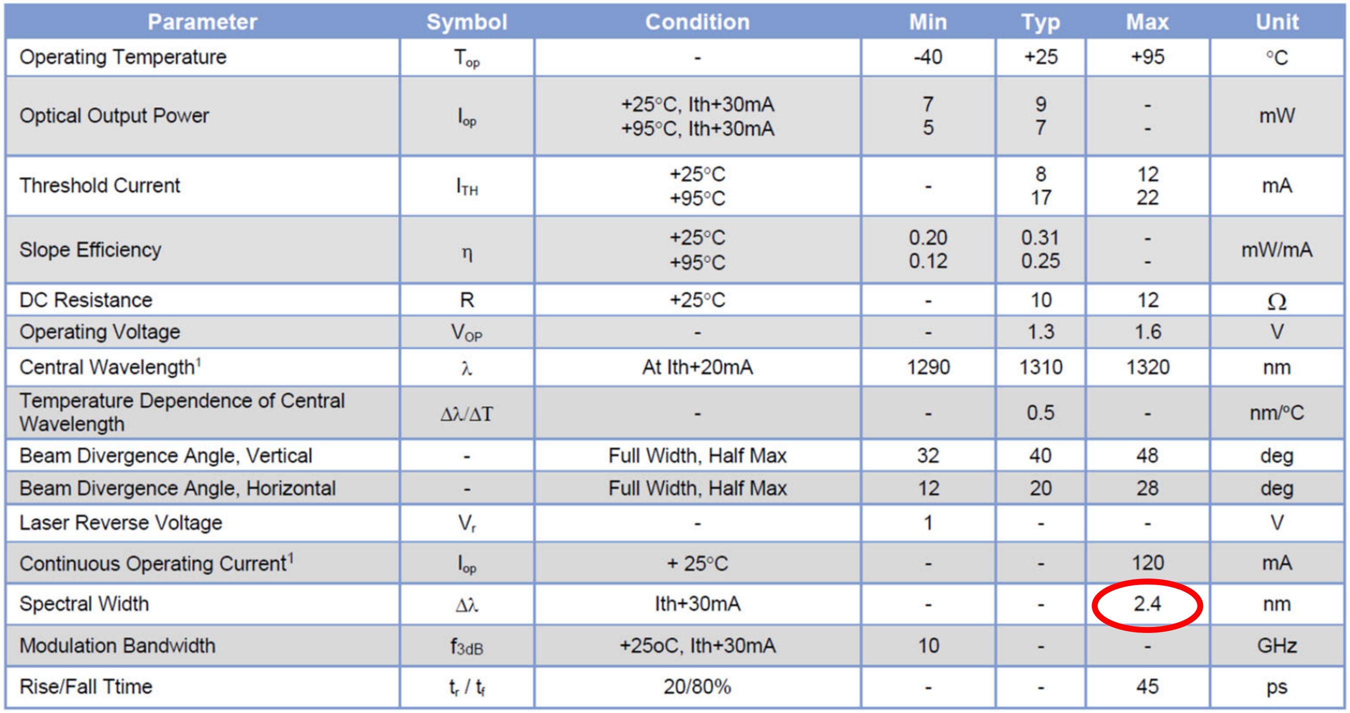
$$\text{Typical } \Delta\lambda_S = 3nm$$

- While FP lasers typically have multiple-longitudinal modes (wavelengths), they can still be designed to have a single transversal mode to couple efficiently into a single-mode fiber

10Gb/s Fabry-Perot Laser Example

[Emcore]





Parameter	Symbol	Condition	Min	Typ	Max	Unit
Operating Temperature	T_{op}	-	-40	+25	+95	°C
Optical Output Power	I_{op}	+25°C, Ith+30mA +95°C, Ith+30mA	7 5	9 7	- -	mW
Threshold Current	I_{TH}	+25°C +95°C	-	8 17	12 22	mA
Slope Efficiency	η	+25°C +95°C	0.20 0.12	0.31 0.25	- -	mW/mA
DC Resistance	R	+25°C	-	10	12	Ω
Operating Voltage	V_{OP}	-	-	1.3	1.6	V
Central Wavelength[1]	λ	At Ith+20mA	1290	1310	1320	nm
Temperature Dependence of Central Wavelength	$\Delta\lambda/\Delta T$	-	-	0.5	-	nm/°C
Beam Divergence Angle, Vertical	-	Full Width, Half Max	32	40	48	deg
Beam Divergence Angle, Horizontal	-	Full Width, Half Max	12	20	28	deg
Laser Reverse Voltage	V_r	-	1	-	-	V
Continuous Operating Current[1]	I_{op}	+ 25°C	-	-	120	mA
Spectral Width	$\Delta\lambda$	Ith+30mA	-	-	2.4	nm
Modulation Bandwidth	f_{3dB}	+25oC, Ith+30mA	10	-	-	GHz
Rise/Fall Ttime	t_r / t_f	20/80%	-	-	45	ps

- Typically used in uncooled applications, where tight wavelength control is not necessary
- Used primarily at 1310nm were dispersion is low

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Bragg Reflections

[Kazovsky]

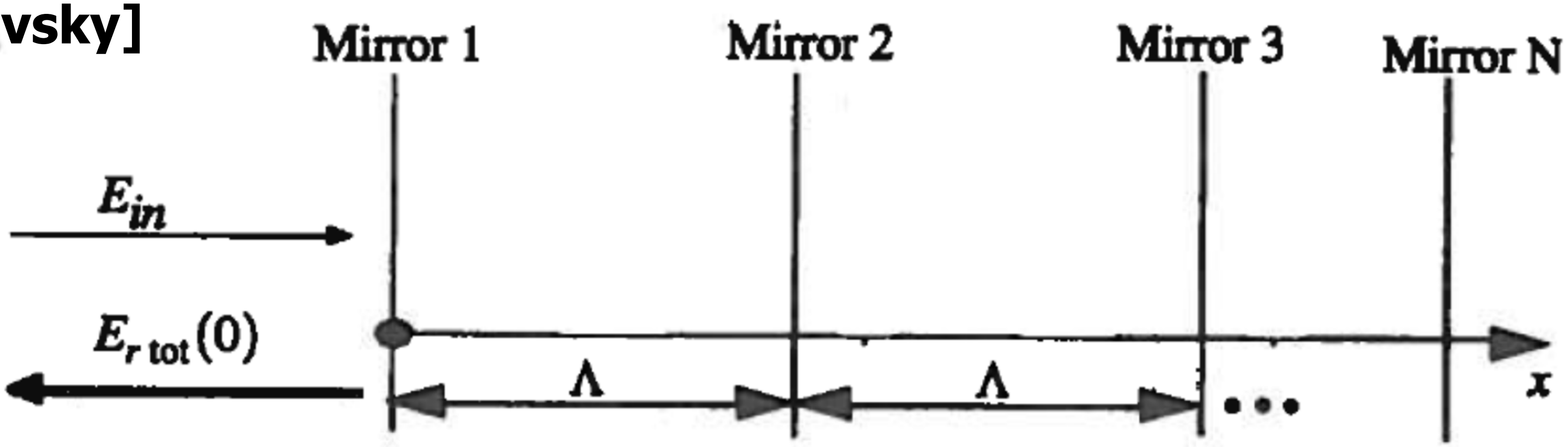


Figure 1.43 The incident wave E_{in} travels through N partially (and weakly) reflective mirrors. At each mirror, the wave is partially transmitted and partially reflected.

$$E_{r1}(0) = E_{in}(0) \cdot r; \quad E_{t1}(0) = E_{in}(0) \cdot t$$

$$E_{r2}(\Lambda) = E_{t1}(0) \cdot r \cdot e^{-j\beta\Lambda}; \quad E_{t2}(\Lambda) = E_{t1}(0) \cdot t \cdot e^{-j\beta\Lambda}$$

$$E_{r3}(2\Lambda) = E_{t2}(\Lambda) \cdot r \cdot e^{-j\beta\Lambda}; \quad E_{t3}(2\Lambda) = E_{t2}(\Lambda) \cdot t \cdot e^{-j\beta\Lambda}$$

$$\vdots$$

$$E_{rN}[(N-1)\Lambda] = E_{t(N-1)}[(N-2)\Lambda] \cdot r \cdot e^{-j\beta\Lambda};$$

$$E_{tN}[(N-1)\Lambda] = E_{t(N-1)}[(N-2)\Lambda] \cdot t \cdot e^{-j\beta\Lambda}$$

$$E_{rtot}(0) = rE_{in}(0) \cdot \frac{1-M^N}{1-M}$$

$$\text{where} \quad M \equiv t^2 e^{-2j\beta\Lambda}$$

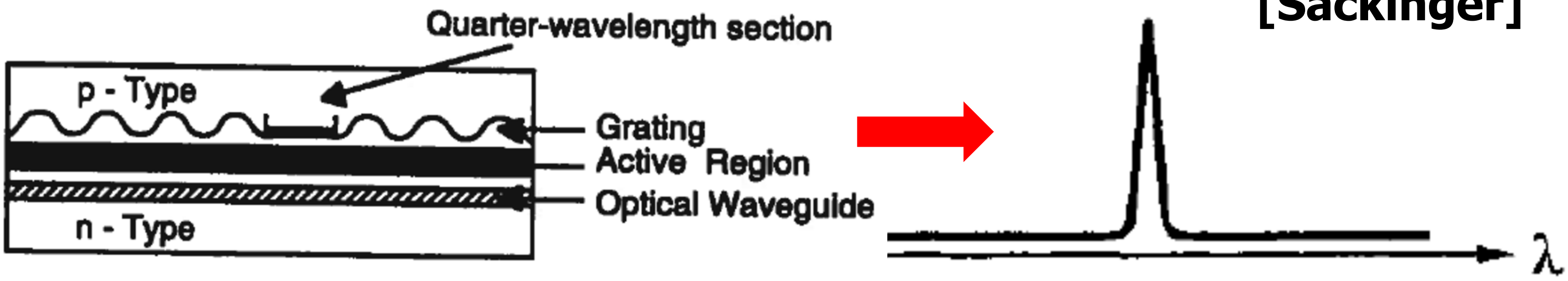
The condition for strong reflections (Bragg condition)

$$\boxed{2\Lambda = \mathrm{m}\lambda}$$

Distributed-Feedback (DFB) Laser

[Kazovsky]

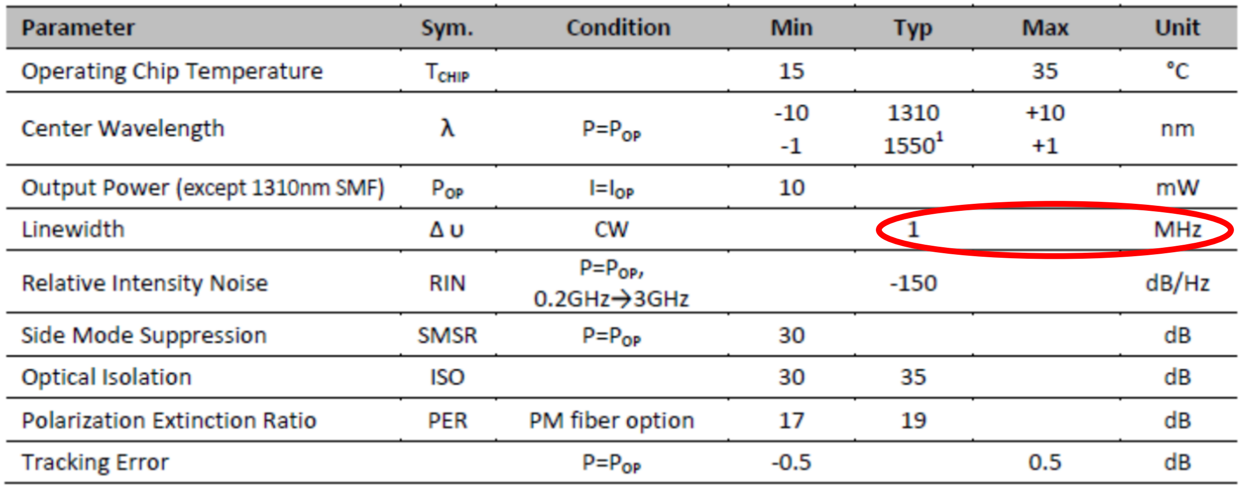
[Sackinger]



- DFBs have a grating etched throughout the cavity, except for a quarter-wavelength shifted section which forces a single longitudinal mode
- This results in a vary narrow linewidth Typical $\Delta\lambda_S < 1pm$
- With direct modulation, the linewidth broadens due to the AM sidebands and chirp
- Since DFB lasers have overlapping gain and grating sections, when the current changes both the output power and frequency change simultaneously, causing chirp

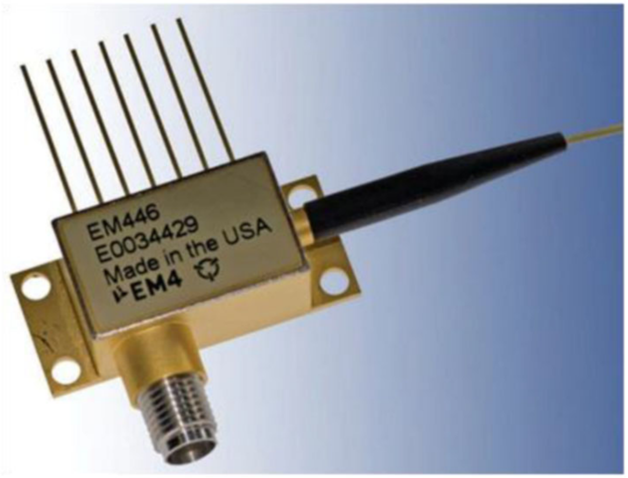
10GHz DFB Laser Example

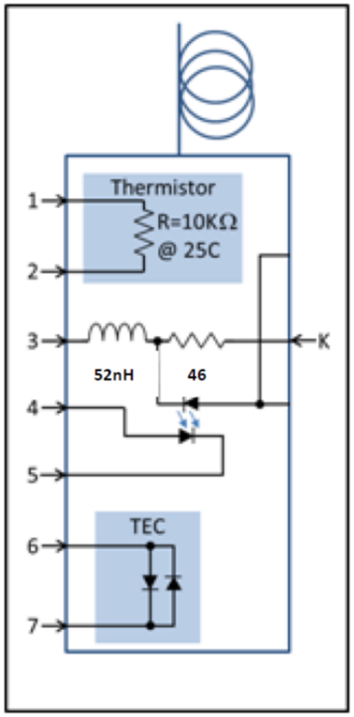
[Gooch & Housego]



Parameter	Sym.	Condition	Min	Typ	Max	Unit
Operating Chip Temperature	T_{CHIP}		15		35	°C
Center Wavelength	λ	$P=P_{OP}$	-10 -1	1310 1550[1]	+10 +1	nm
Output Power (except 1310nm SMF)	P_{OP}	$I=I_{OP}$	10			mW
Linewidth	$\Delta\upsilon$	CW		1		MHz
Relative Intensity Noise	RIN	$P=P_{OP}$, 0.2GHz→3GHz		-150		dB/Hz
Side Mode Suppression	SMSR	$P=P_{OP}$	30			dB
Optical Isolation	ISO		30	35		dB
Polarization Extinction Ratio	PER	PM fiber option	17	19		dB
Tracking Error		$P=P_{OP}$	-0.5		0.5	dB

- Very tight linewidth, 1MHz at 1550nm is 8fm!!
- As the lasing wavelength is sensitive to temperature (~0.1nm/°C), DFB lasers often include thermal control





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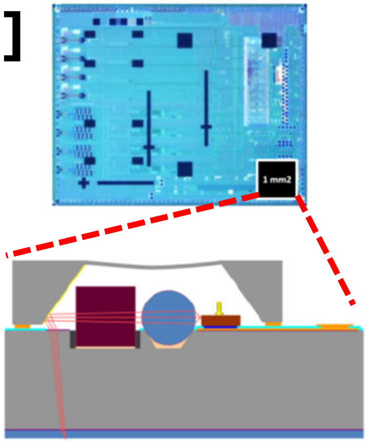
Laser Integration Strategy

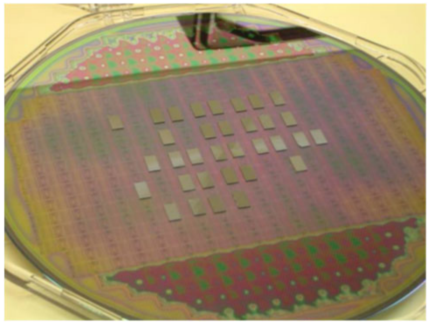
- With the rise of silicon photonic integrated circuits, there are various approaches to laser integration
- Stand-alone laser
  - Laser is separate from the silicon PIC
  - ☺ Enables testing before integration
  - ☹ Requires separate assembly of each laser

[Luxtera]



- Hybrid laser
  - Involves the bonding of a III-V gain material onto a silicon waveguide
  - ☺ Allows for wafer-scale processing
  - ☹ Lasers can't be tested before assembly

[Bowers]



DFB Hybrid Silicon Laser

[Zhang Opt Exp 2014]

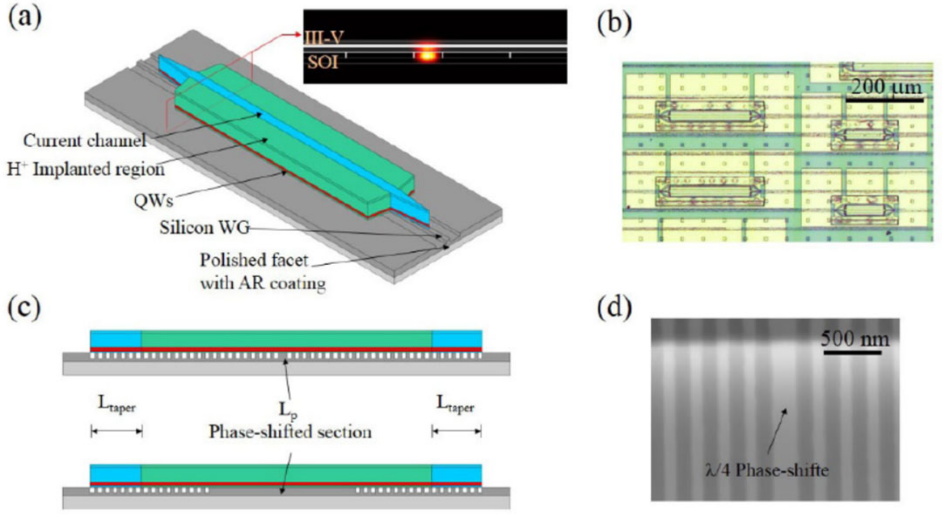


Fig. 1. Illustration of (a) a hybrid DFB laser; (b) a microscope image of the laser chip after fabrication; (c) a schematic lateral view with a grating on the waveguide; (d) SEM image of a first order grating with a λ/4 phase shift.

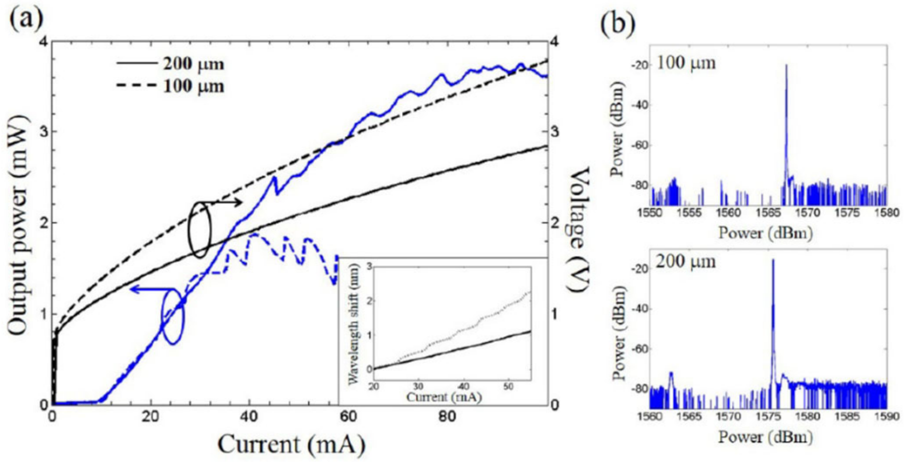
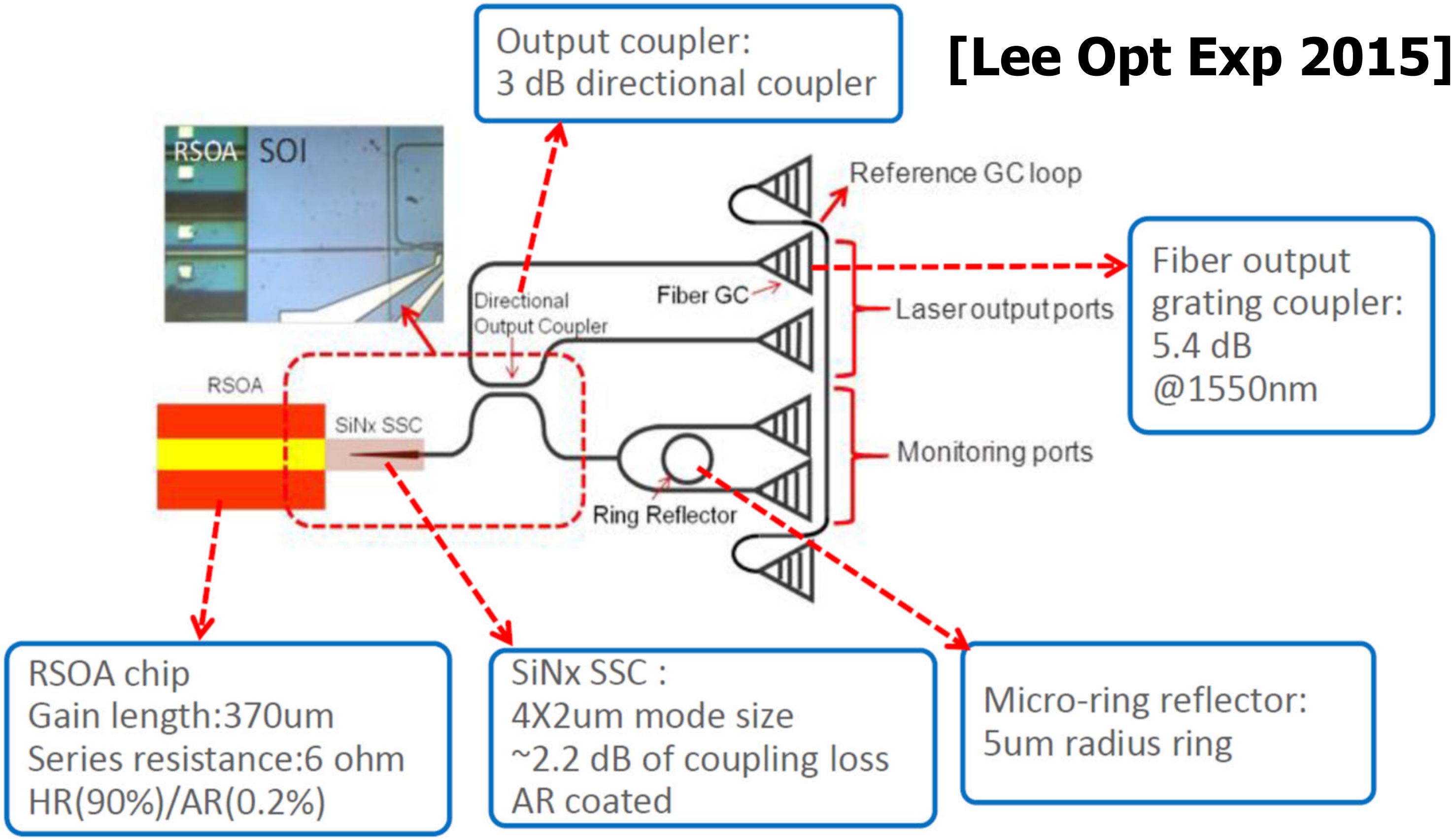


Fig. 3. (a) L-I and I-V curves of 200 μm (solid line) and 100 μm (dash line) hybrid DFB lasers with quarter phase-shifted section and (b) the corresponding lasing spectrum at 20mA injection current; The insert in (a) is the central wavelength shift with injection current.

- Optical gain provided by III-V (InAlGaAs) bonded onto silicon waveguide
- Should enable high coupling efficiency with subsequent modulators on the same PIC
- Achieved a wall-plug efficiency of ~2% ☹

External-Cavity Hybrid Silicon Laser

[Lee Opt Exp 2015]



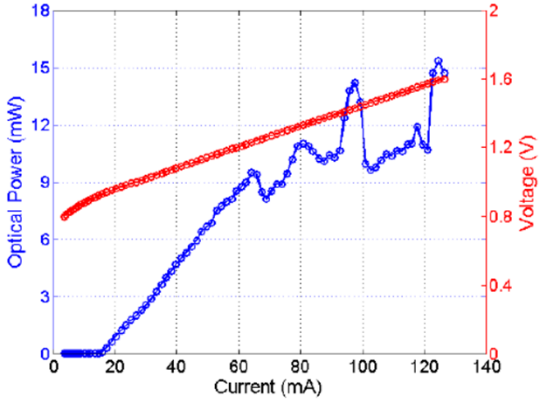
Output coupler:
3 dB directional coupler

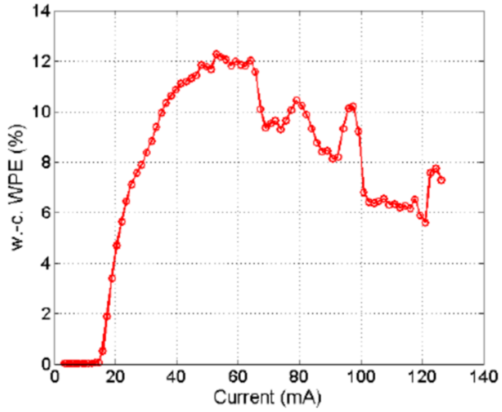
Fiber output grating coupler:
5.4 dB
@1550nm

RSOA chip
Gain length:370um
Series resistance:6 ohm
HR(90%)/AR(0.2%)

SiNx SSC :
4X2um mode size
~2.2 dB of coupling loss
AR coated

Micro-ring reflector:
5um radius ring





- External reflective semiconductor optical amplifier (RSOA) provides gain
- Heating the ring reflector provides 8nm tuning range
- Achieves a wall-plug efficiency of 12.2%

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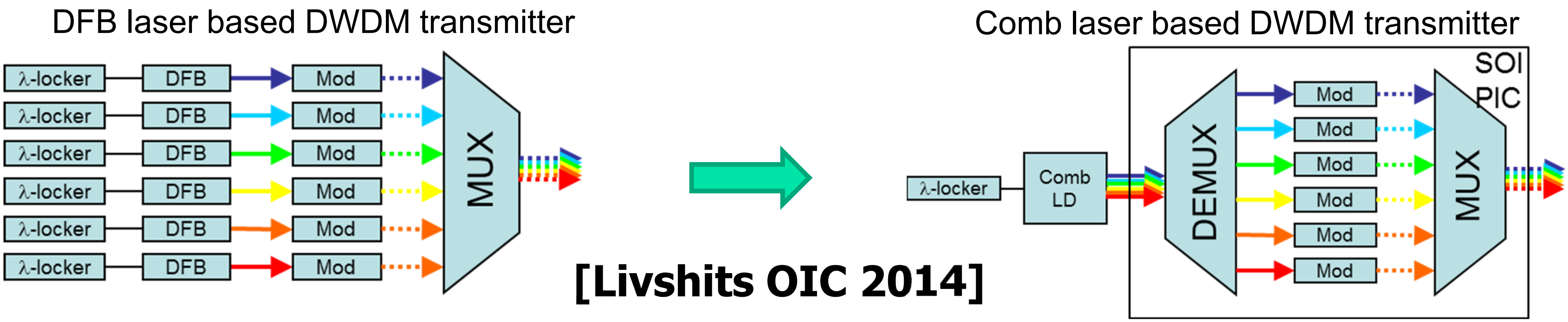
DWDM Laser Sources

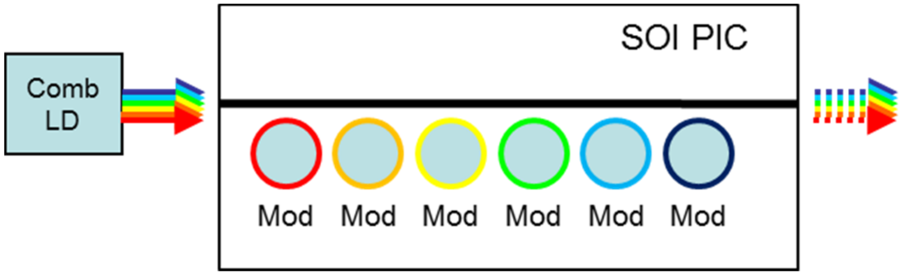


DFB laser based DWDM transmitter

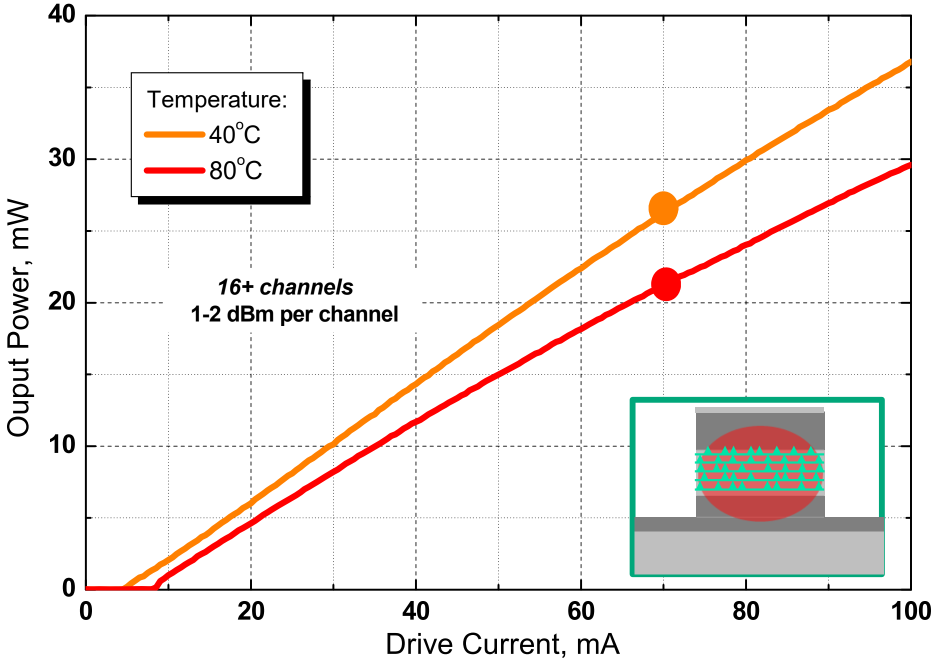
Comb laser based DWDM transmitter

[Livshits OIC 2014]

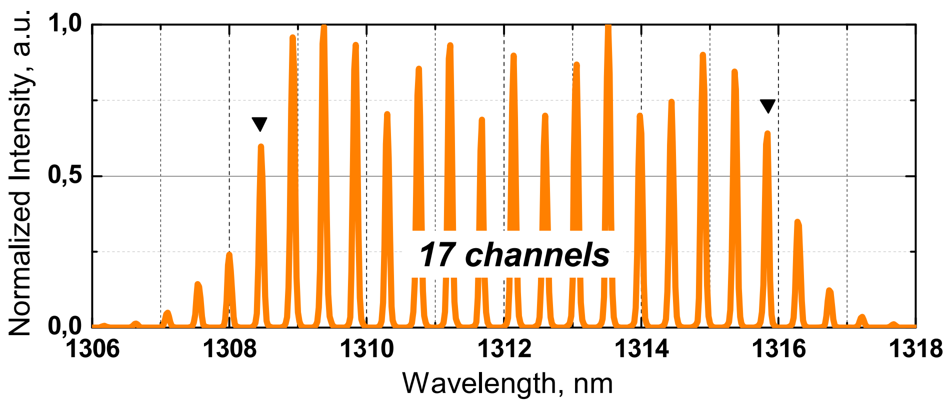
- A dense wavelength-division multiplexed (DWDM) system requires the integration of many DFB lasers that have accurate channel spacing
- A single "comb" laser can produce these wavelengths with stable channel spacing
- An attractive solution is to use a comb laser with ring modulators that provide inherent wavelength multiplexing



Quantum Dot Fabry-Perot Comb Laser



[Livshits OIC 2014]



- 80GHz channel spacing
- 1.5-1.8mW per channel
- Requires ~70mA current

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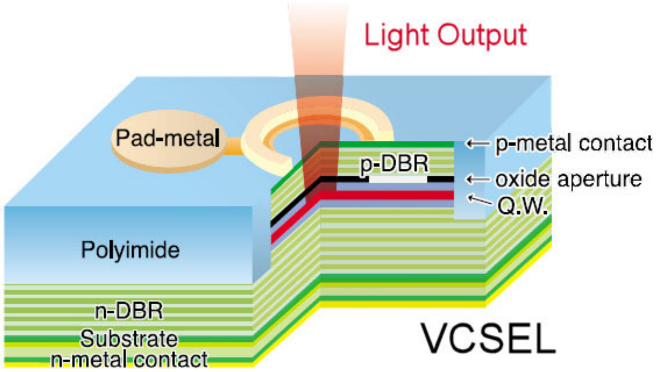
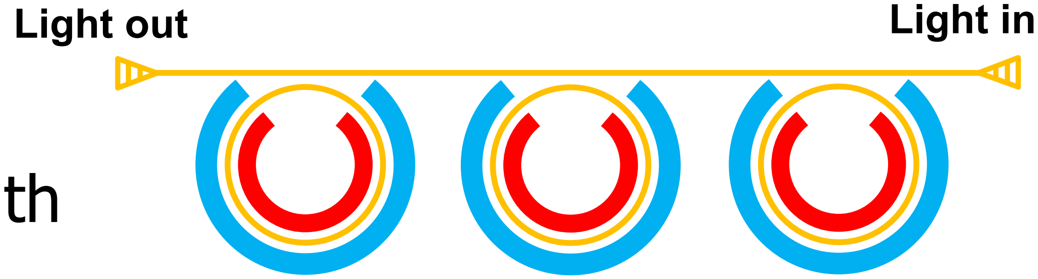
Compact Optical Devices

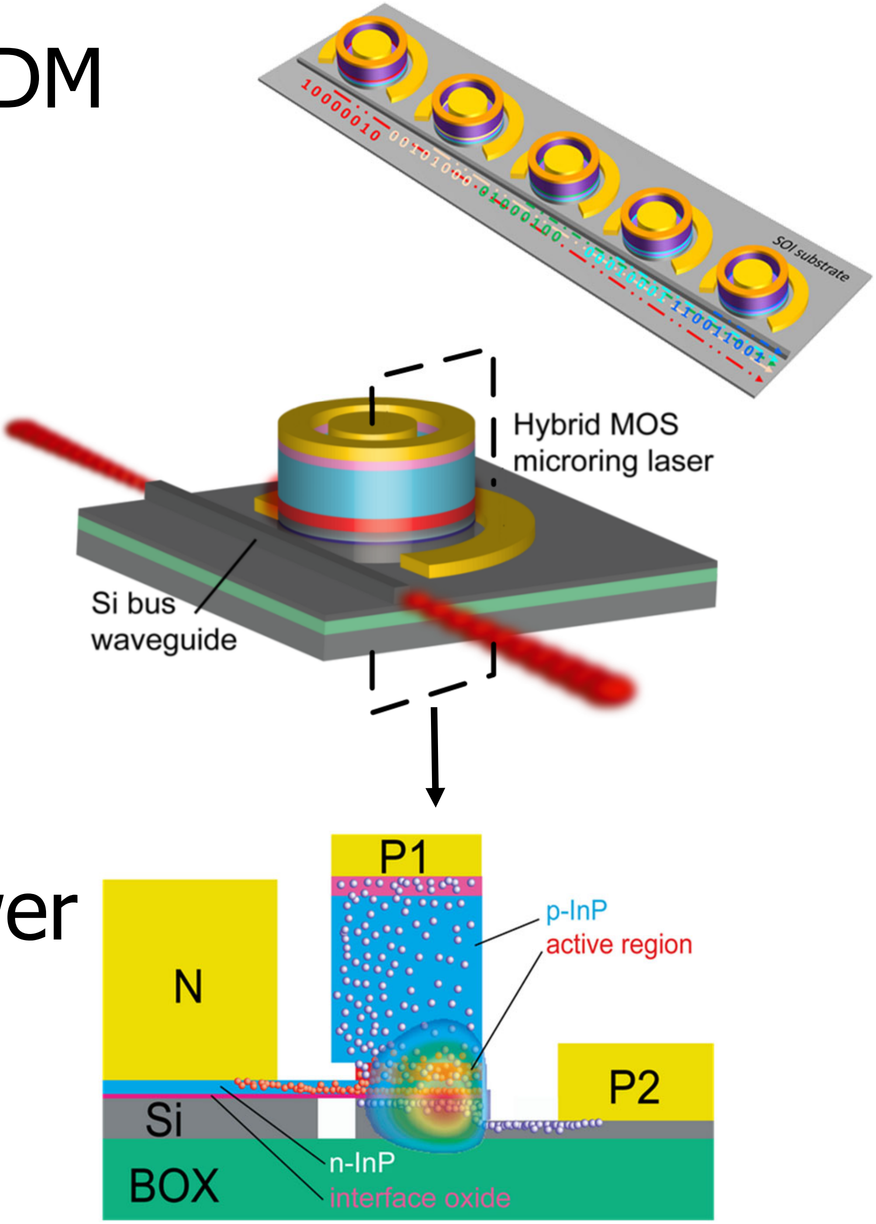
- VCSEL
  - Laser source
  - Good modulation bandwidth
  - Relatively Low power consumption
  - Complicated setup to implement WDM
- Microring Modulator
  - Require external laser source
    - Reduced integration level
    - Packaging challenges
    - Extra coupling loss
  - Good modulation bandwidth
  - Low power consumption
  - Inherent WDM





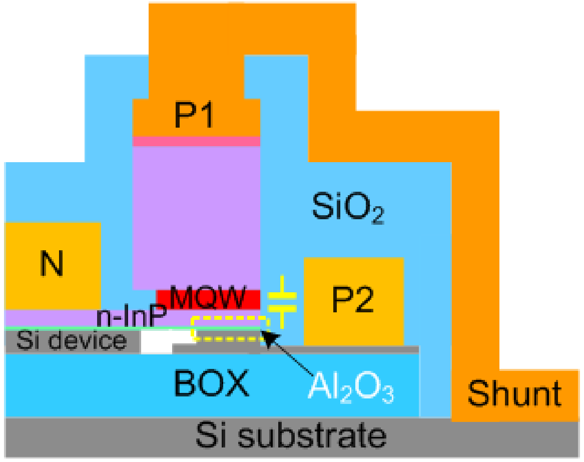
Microring Lasers

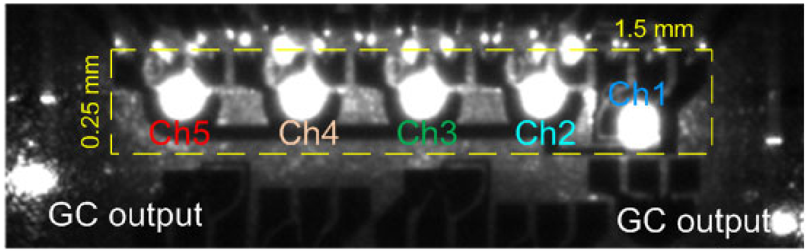
- Laser Source + Inherent WDM
  - Eliminate external laser
  - Dense integration
  - Reduced Coupling loss
  - Easier packaging
  - Low complexity WDM
- Relatively high bandwidth
- Large room to improve power

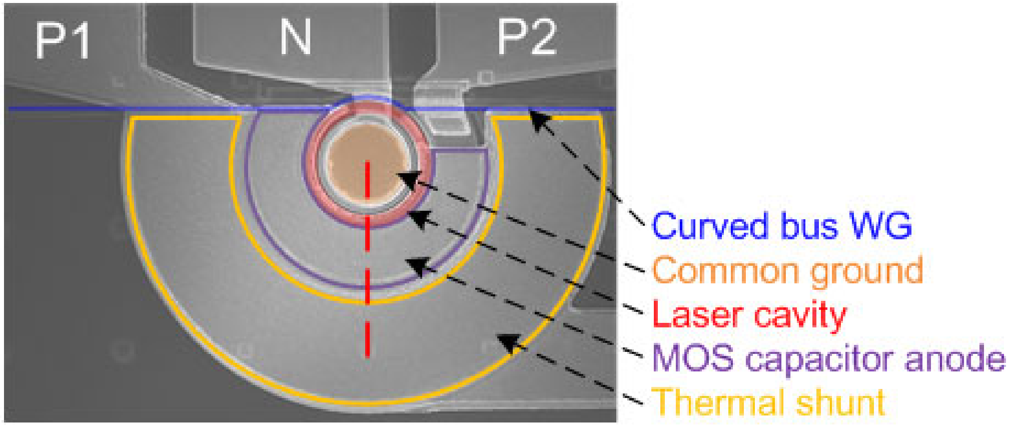


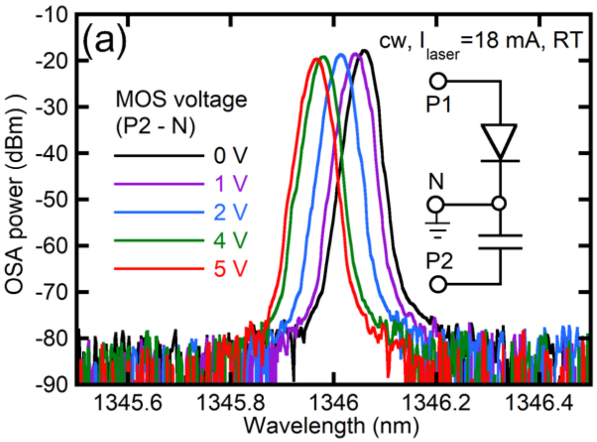
Multi-Channel Hybrid Transmitter Design

- 5-channel hybrid microring laser array
  - D=50 µm, 1310 nm active region
- Novel three-terminal design
  - MOS capacitor integrated for tuning/direct modulation
  - P1 – N: inject carriers into active region
  - P2 – N: bias MOS capacitor
- Integrated thermal shunt
  - efficient self-heating dissipation





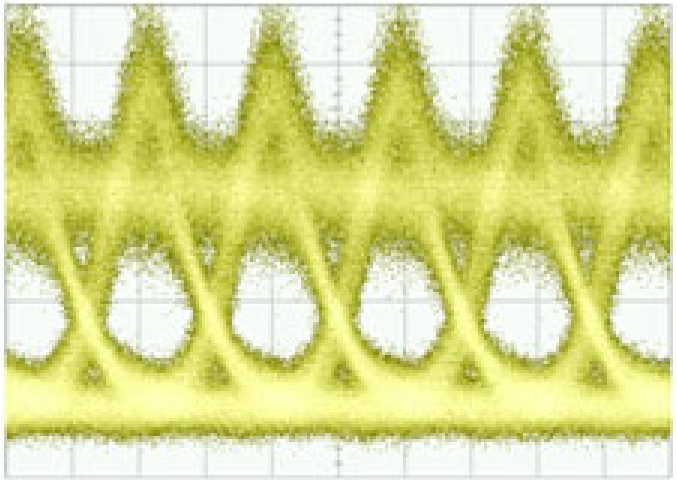


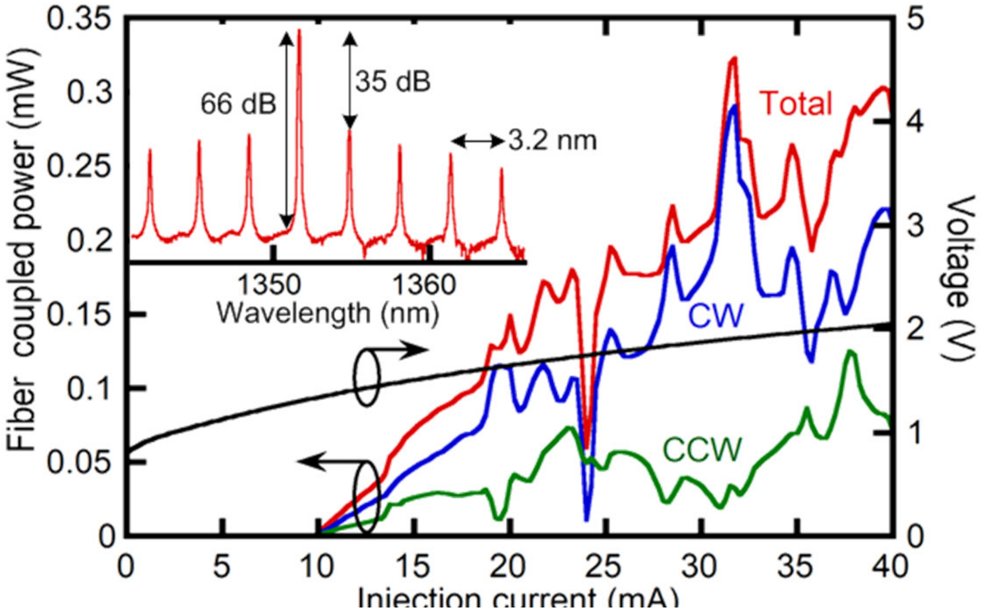


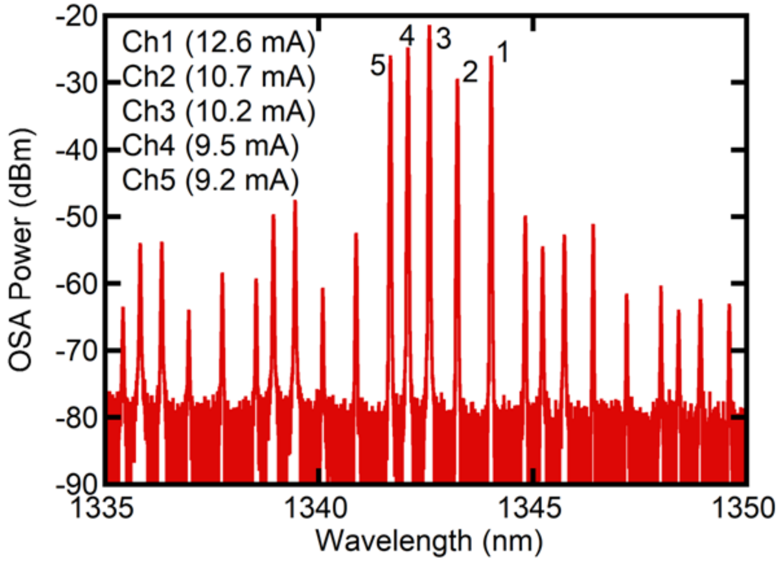
Optical Performance

- Threshold current: 5-10 mA (CW lasing)
- Fiber coupled output power: 0.1-0.3 mW (>10 dB GC loss)
- Spectrum
  - 1340-1360 nm
  - Extinction ratio >65 dB, Side-mode suppression ratio > 30 dB
- Direct modulation: 10.5 Gb/s (bench-top instrument driver)

10.5 Gb/s

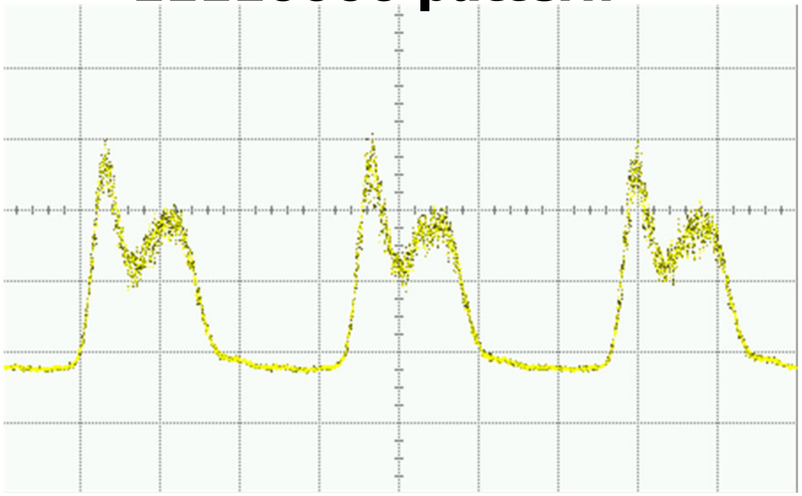




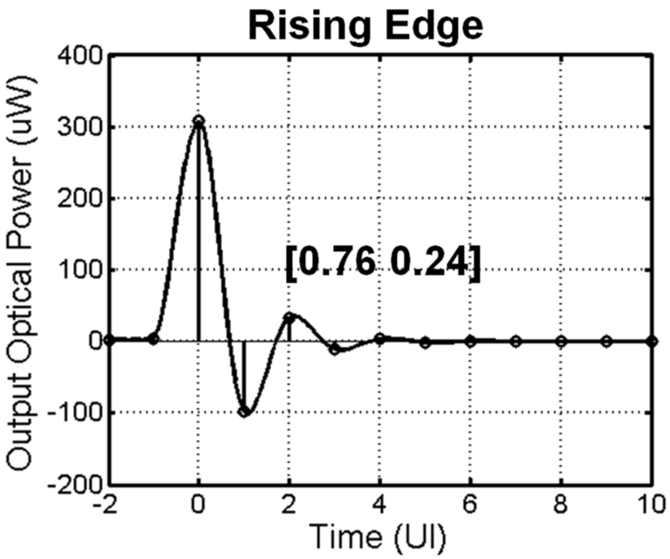


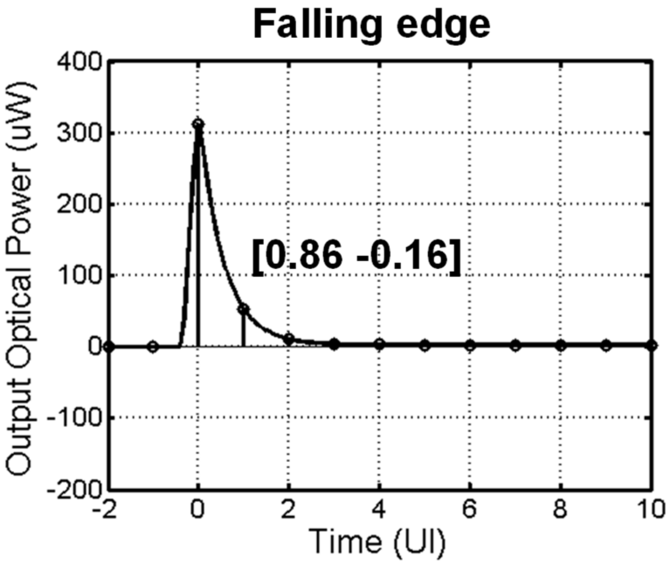
Microring Laser Dynamic Behavior

Measured response to 11110000 pattern



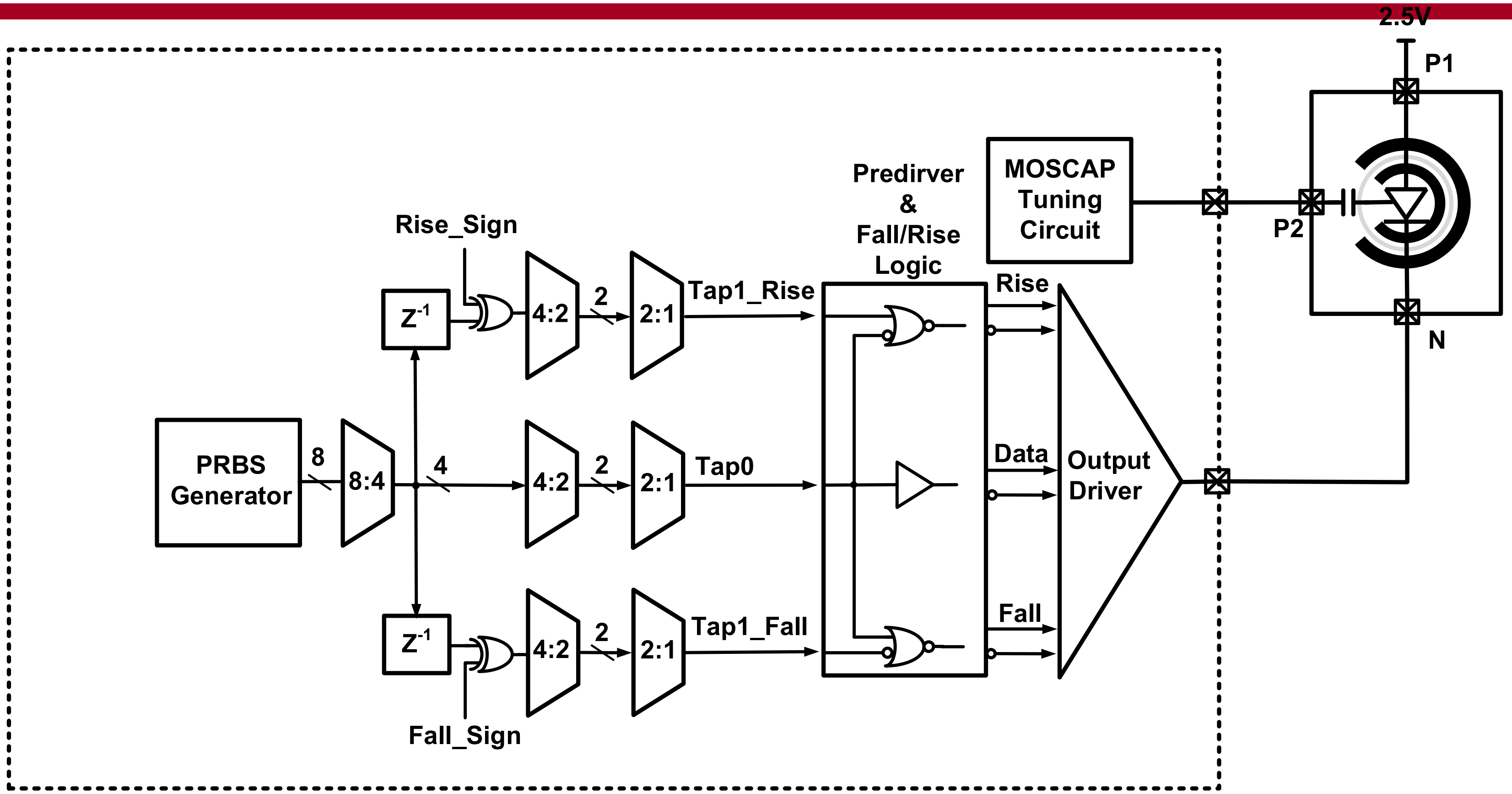
Simulated pulse response





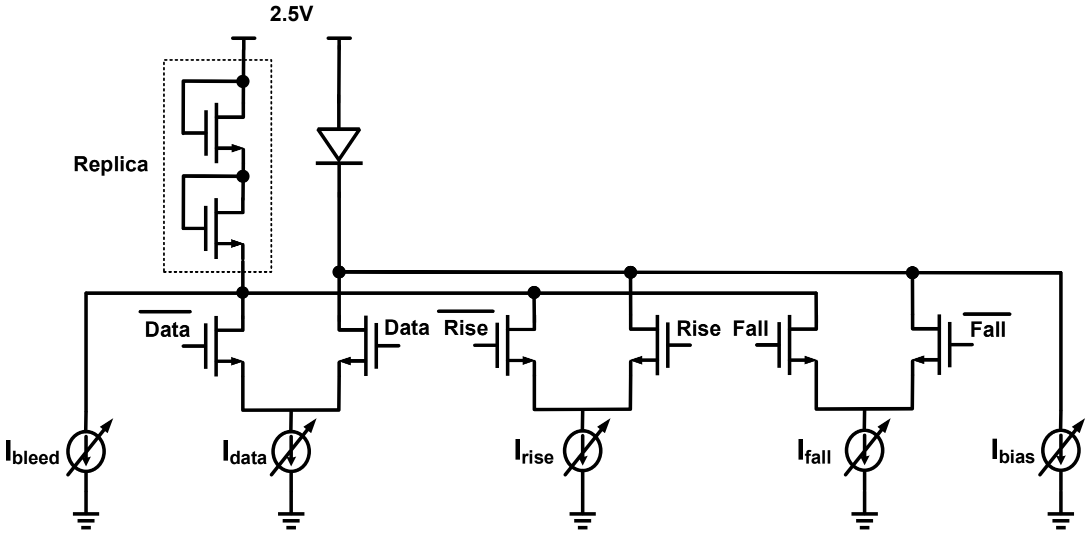
- Rising pulse response
  - Fast & underdamped
- Falling edge
  - Slow & overdamped
- Asymmetric EQ required

Driver Data Path



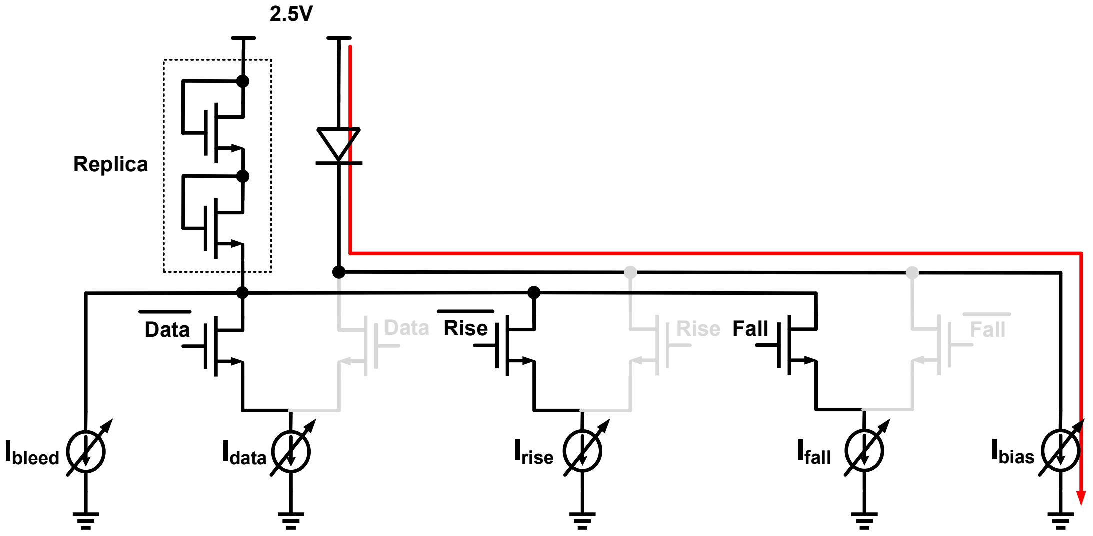
- Half rate architecture
- Pre-driver generate fall/rise pulses with independent sign
- Current mode output driver w/ replica reduces the supply noise

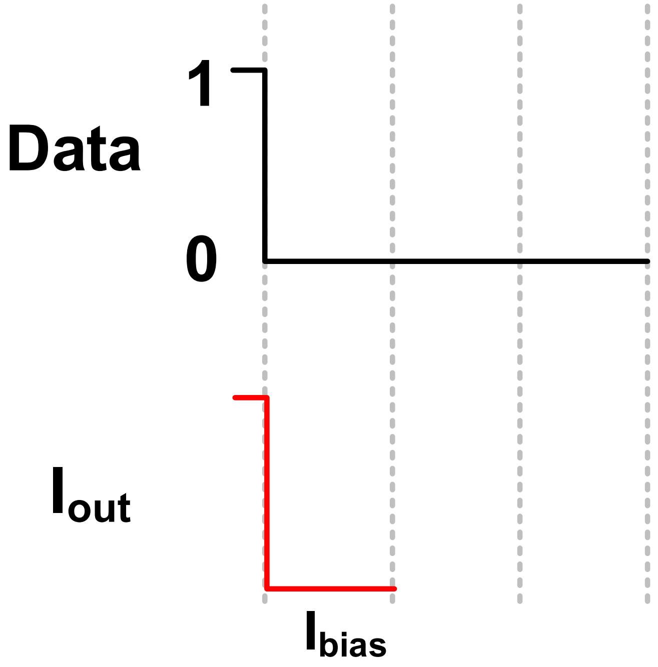
Output Driver



- I_{bias}: Controls laser bandwidth
- I_{data}: Controls current swing
- I_{fall}: Reduce/increase current on data fall depending on tap sign (FFE)
- I_{rise}: Reduce/increase current on data rise depending on tap sign (FFE)
- I_{bleed}: Provides biasing for the replica

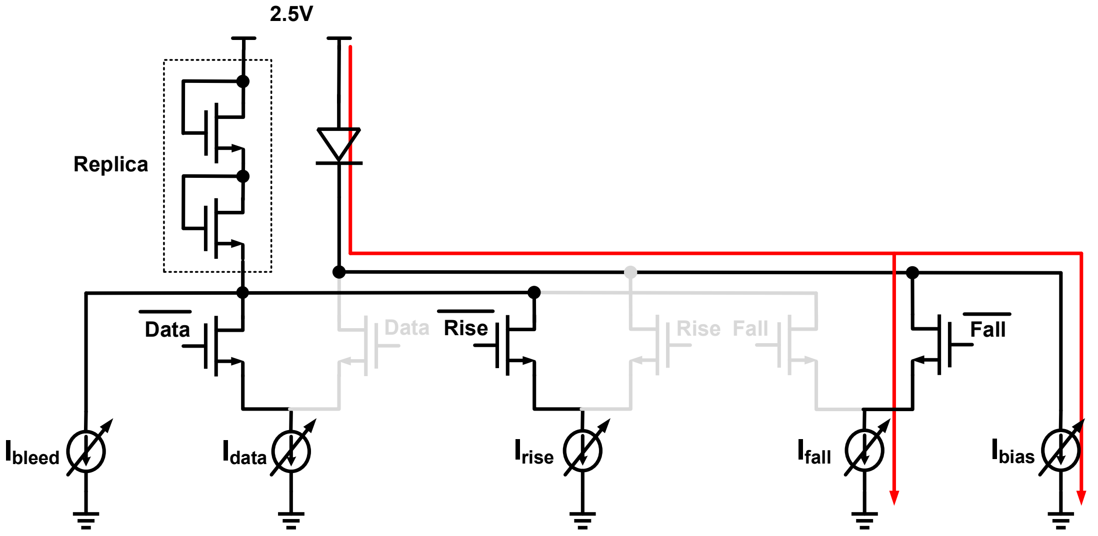
Sending a "0"

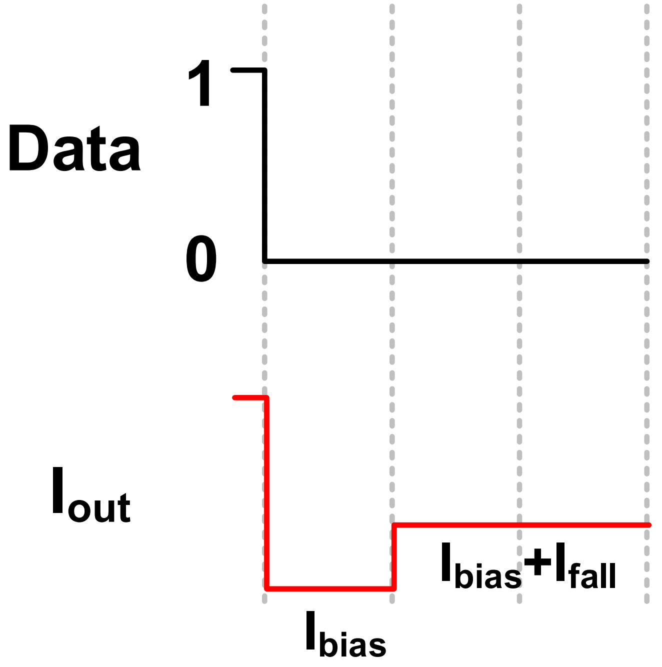




- Negative tap sign (high pass)
  - Falling edge: I_{bias}
  - Long run: $I_{bias}+I_{fall}$
- Positive tap sign (low pass)
  - Falling edge: $I_{bias}+I_{fall}$
  - Long run: I_{bias}

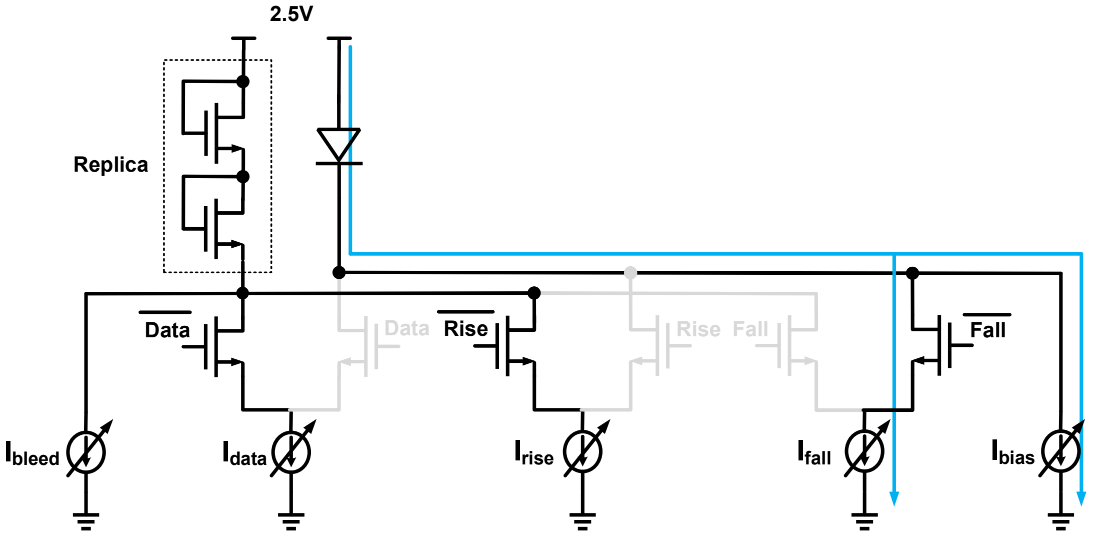
Sending a "0"

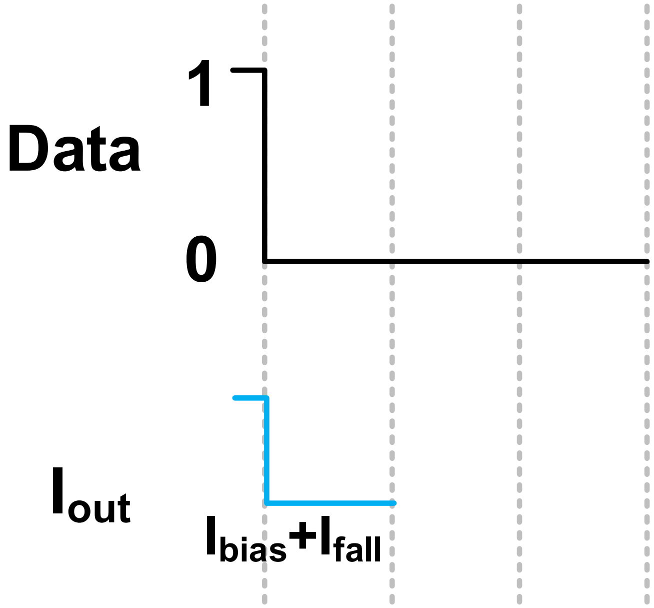




- Negative tap sign (high pass)
  - Falling edge: I_{bias}
  - Long run: $I_{bias}+I_{fall}$
- Positive tap sign (low pass)
  - Falling edge: $I_{bias}+I_{fall}$
  - Long run: I_{bias}

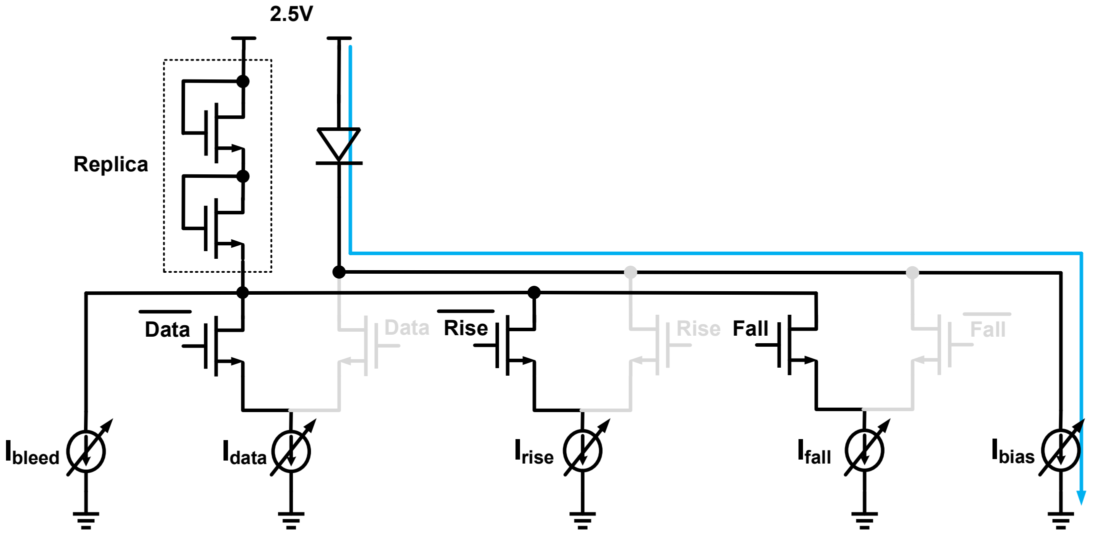
Sending a “0”

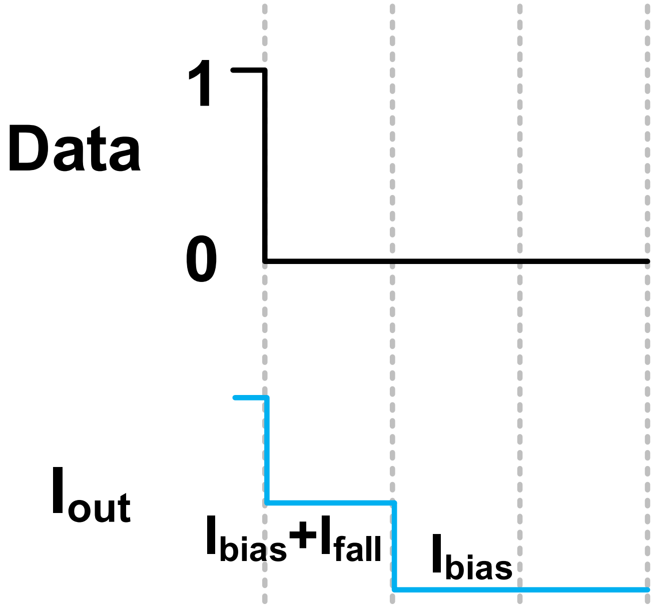




- Negative tap sign (high pass)
  - Falling edge: I_{bias}
  - Long run: $I_{bias}+I_{fall}$
- Positive tap sign (low pass)
  - Falling edge: $I_{bias}+I_{fall}$
  - Long run: I_{bias}

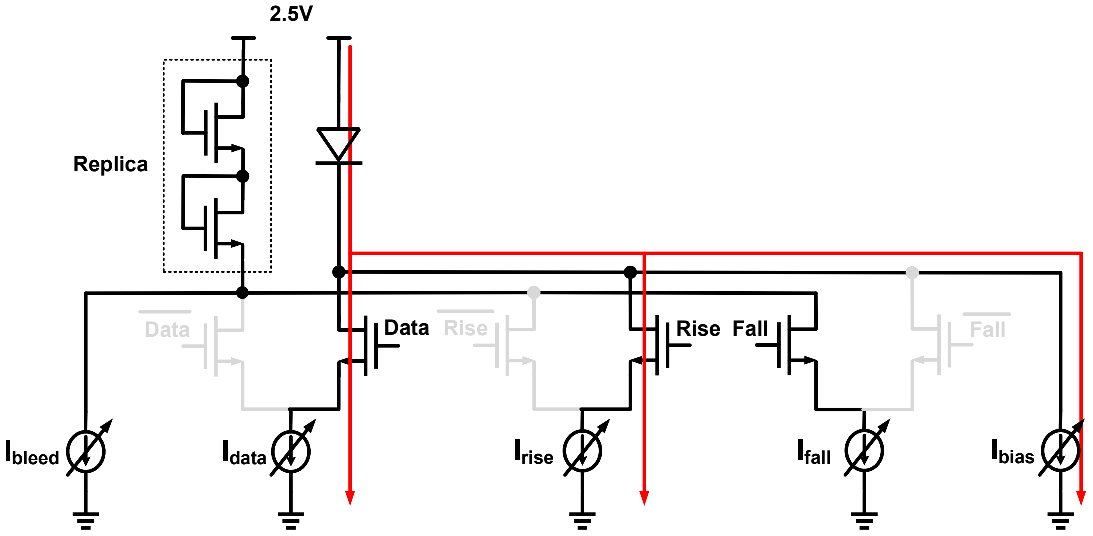
Sending a "0"

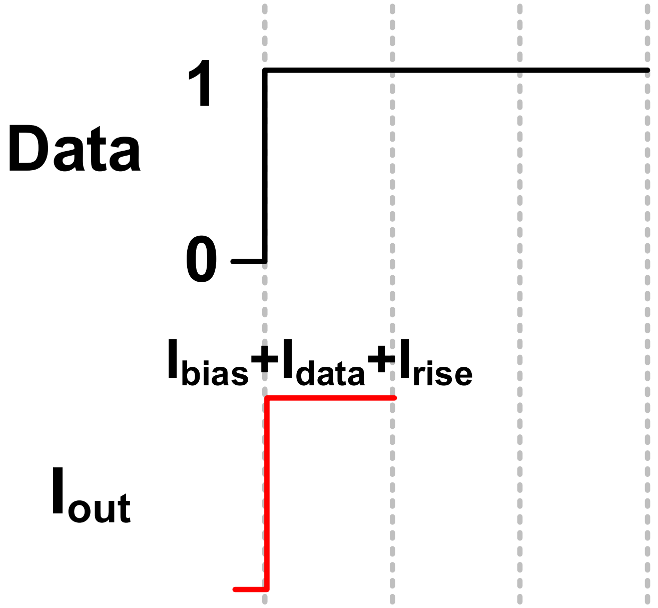




- Negative tap sign (high pass)
  - Falling edge: I_{bias}
  - Long run: $I_{bias}+I_{fall}$
- Positive tap sign (low pass)
  - Falling edge: $I_{bias}+I_{fall}$
  - Long run: I_{bias}

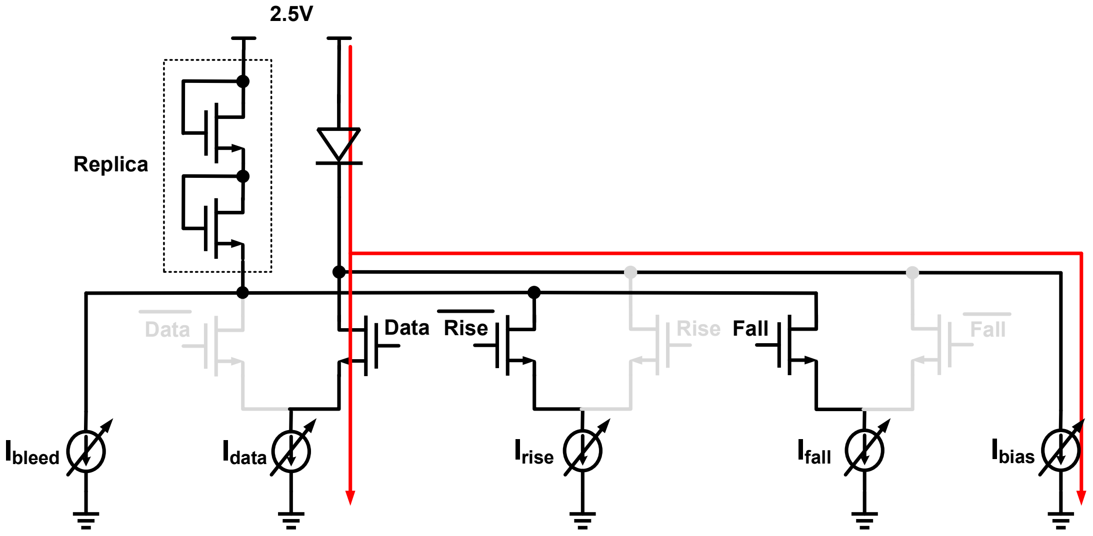
Sending a "1"

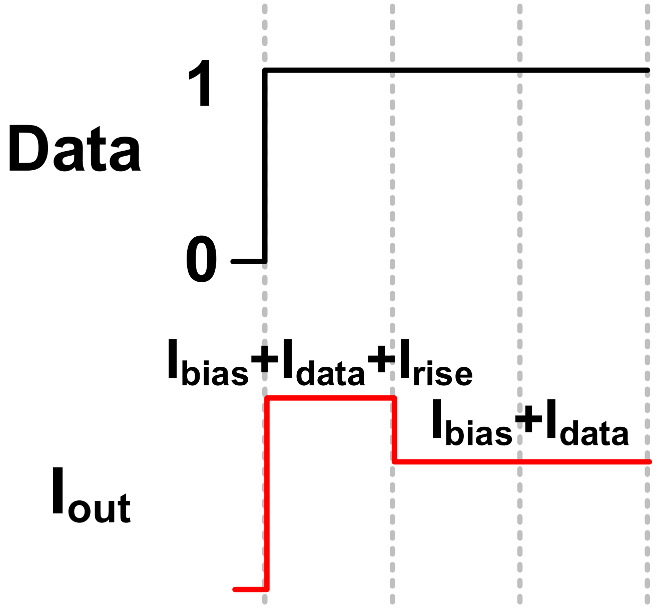




- Negative tap sign (high pass)
  - Rising edge: $I_{bias}+ I_{data}+ I_{rise}$
  - Long run: $I_{bias}+ I_{data}$
- Positive tap sign (low pass)
  - Rising edge: $I_{bias}+ I_{data}$
  - Long run: $I_{bias}+ I_{data}+ I_{rise}$

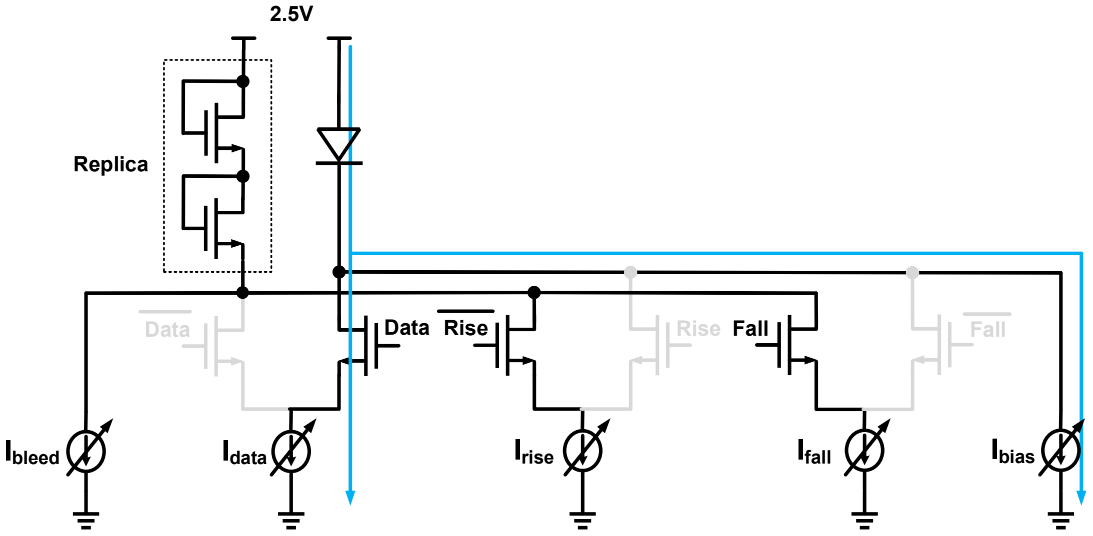
Sending a “1”

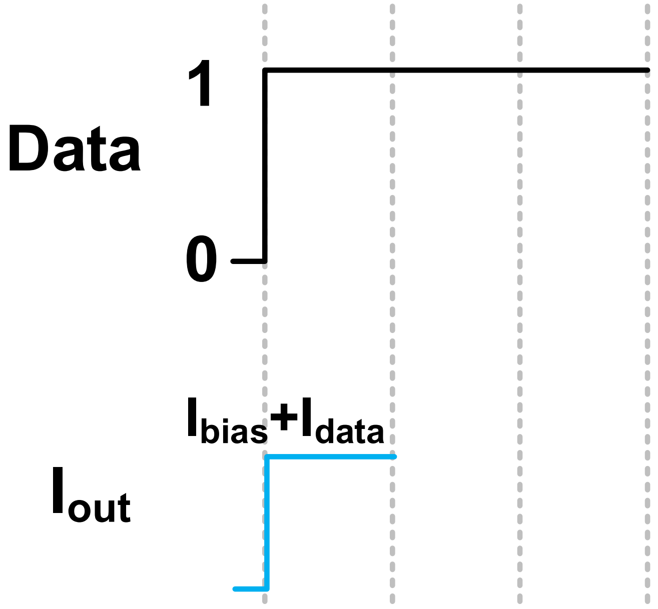




- Negative tap sign (high pass)
  - Rising edge: $I_{bias} + I_{data} + I_{rise}$
  - Long run: $I_{bias} + I_{data}$
- Positive tap sign (low pass)
  - Rising edge: $I_{bias} + I_{data}$
  - Long run: $I_{bias} + I_{data} + I_{rise}$

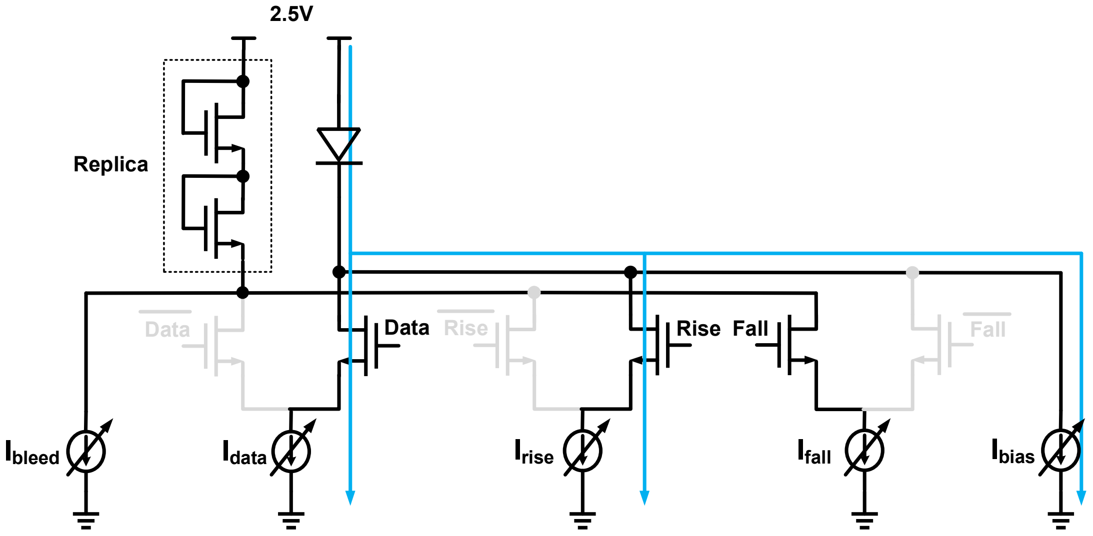
Sending a "1"

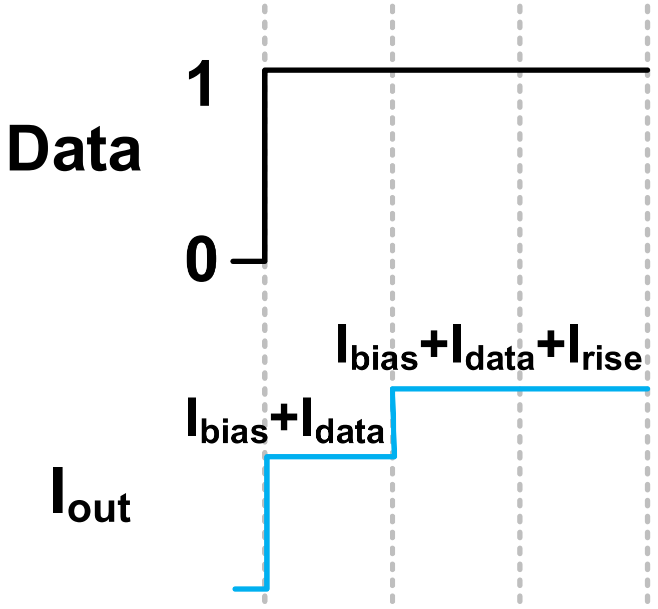




- Negative tap sign (high pass)
  - Rising edge: I_{bias}+ I_{data}+ I_{rise}
  - Long run: I_{bias}+ I_{data}
- Positive tap sign (low pass)
  - Rising edge: I_{bias}+ I_{data}
  - Long run: I_{bias}+ I_{data}+ I_{rise}

Sending a “1”

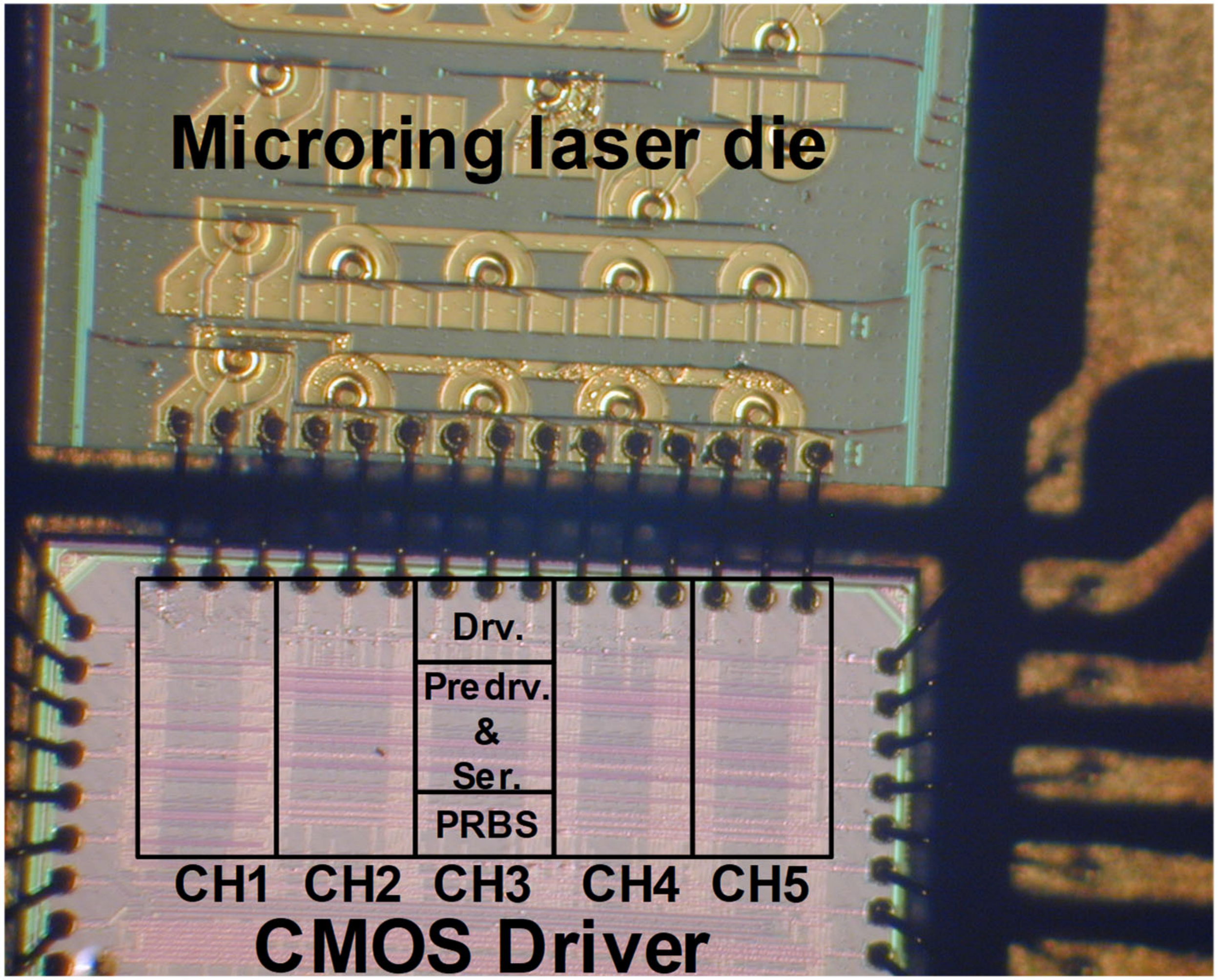




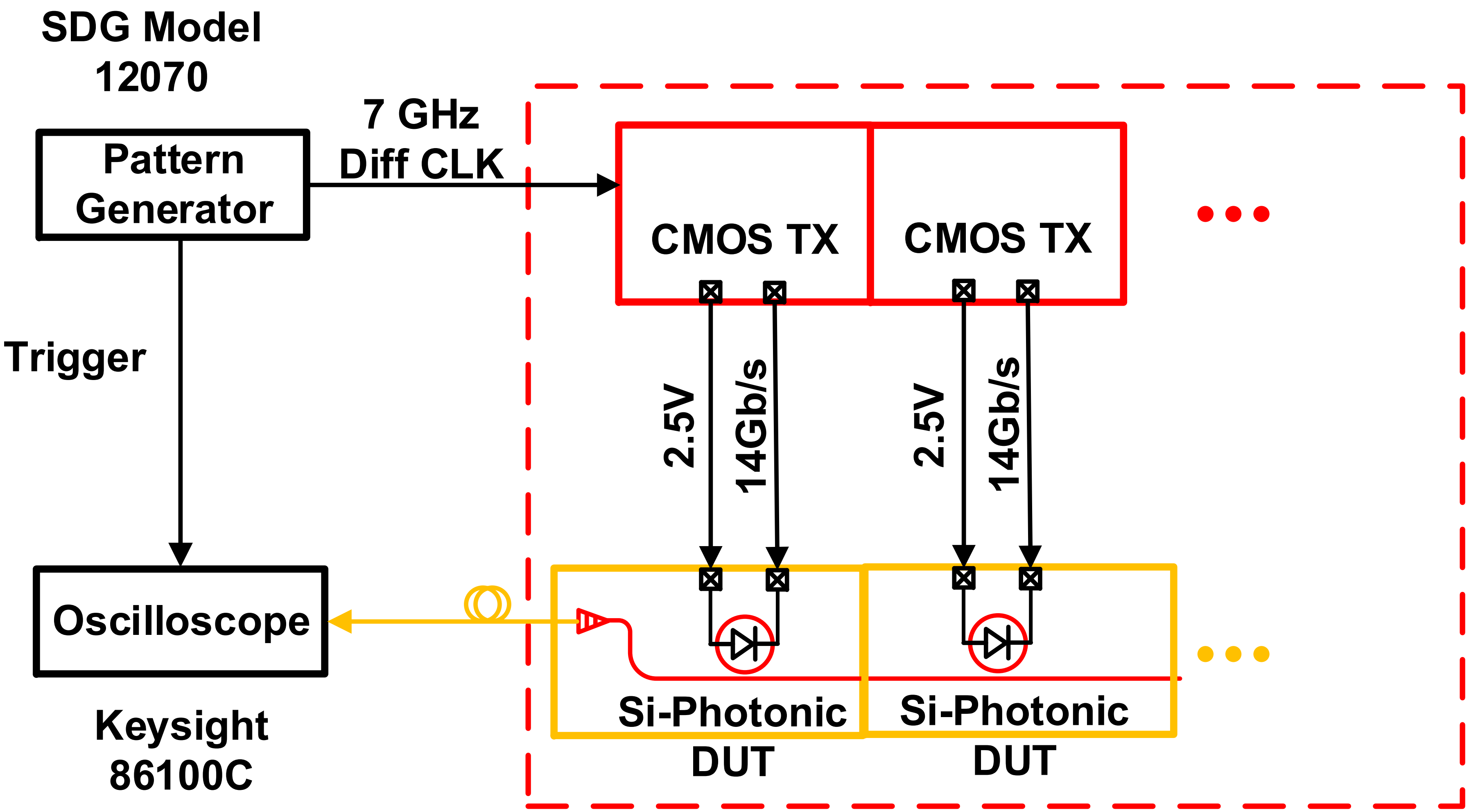
- Negative tap sign (high pass)
  - Rising edge: $I_{bias}+I_{data}+I_{rise}$
  - Long run: $I_{bias}+I_{data}$
- Positive tap sign (low pass)
  - Rising edge: $I_{bias}+I_{data}$
  - Long run: $I_{bias}+I_{data}+I_{rise}$

Die Photo & Hybrid Integration

- Si Photonic IC
  - SOI Process
- CMOS TX
  - GP 65nm CMOS

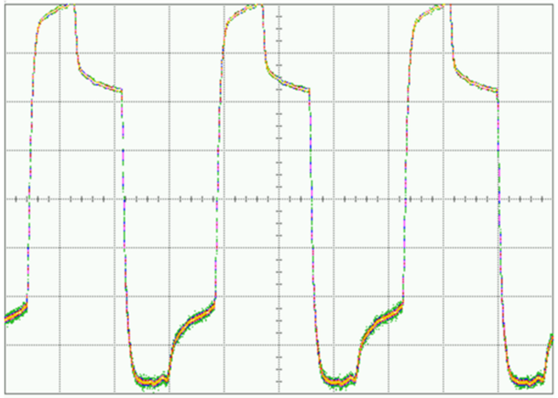


Test Setup

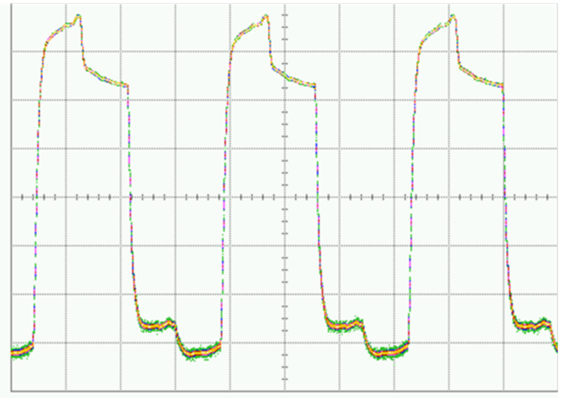

SDG Model
12070
Pattern Generator
7 GHz
Diff CLK
Trigger
Oscilloscope
Keysight
86100C
CMOS TX
CMOS TX
2.5V
14Gb/s
2.5V
14Gb/s
Si-Photonic
DUT
Si-Photonic
DUT

Asymmetric FFE EQ

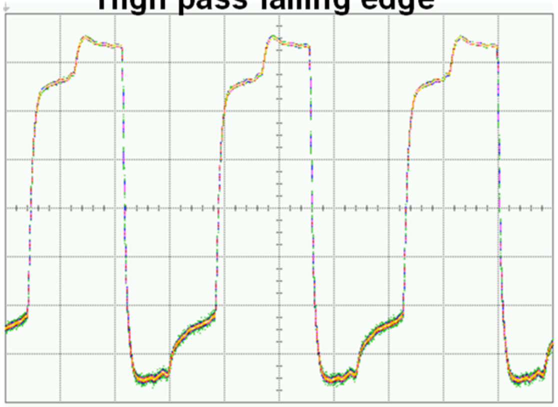
High pass rising edge
High pass falling edge



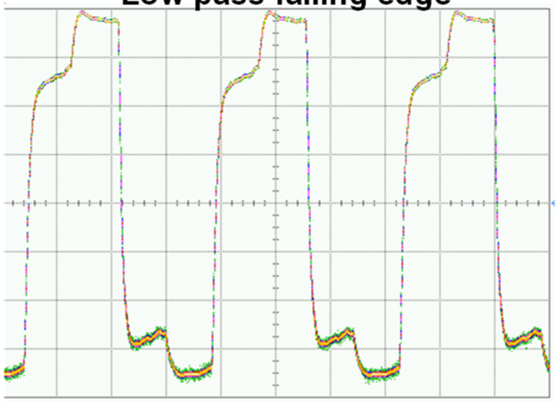
High pass rising edge
Low pass falling edge



Low pass rising edge
High pass falling edge



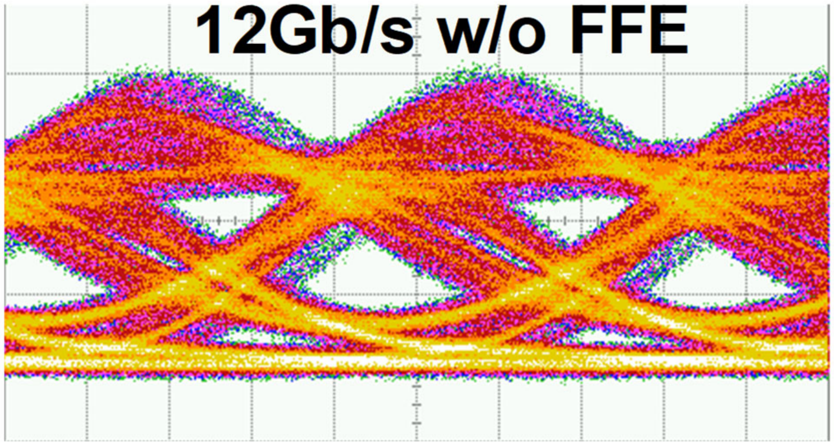
Low pass rising edge
Low pass falling edge



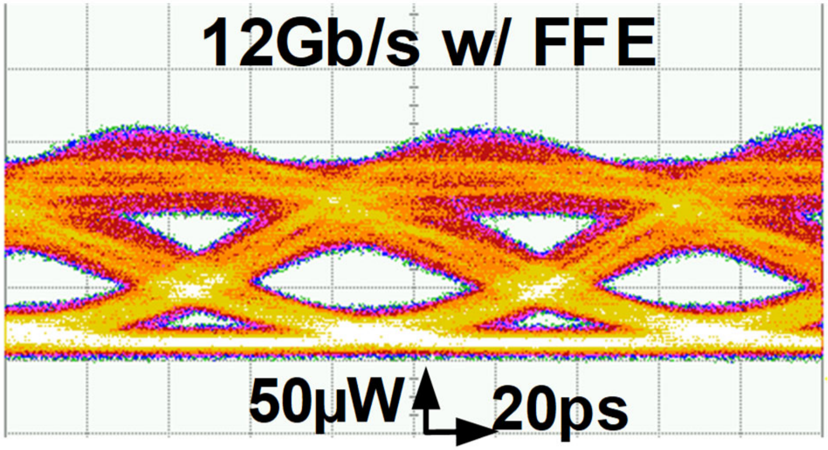
- Measured driver output to 1100 pattern w/ different EQ settings

Asymmetric FFE EQ Effect

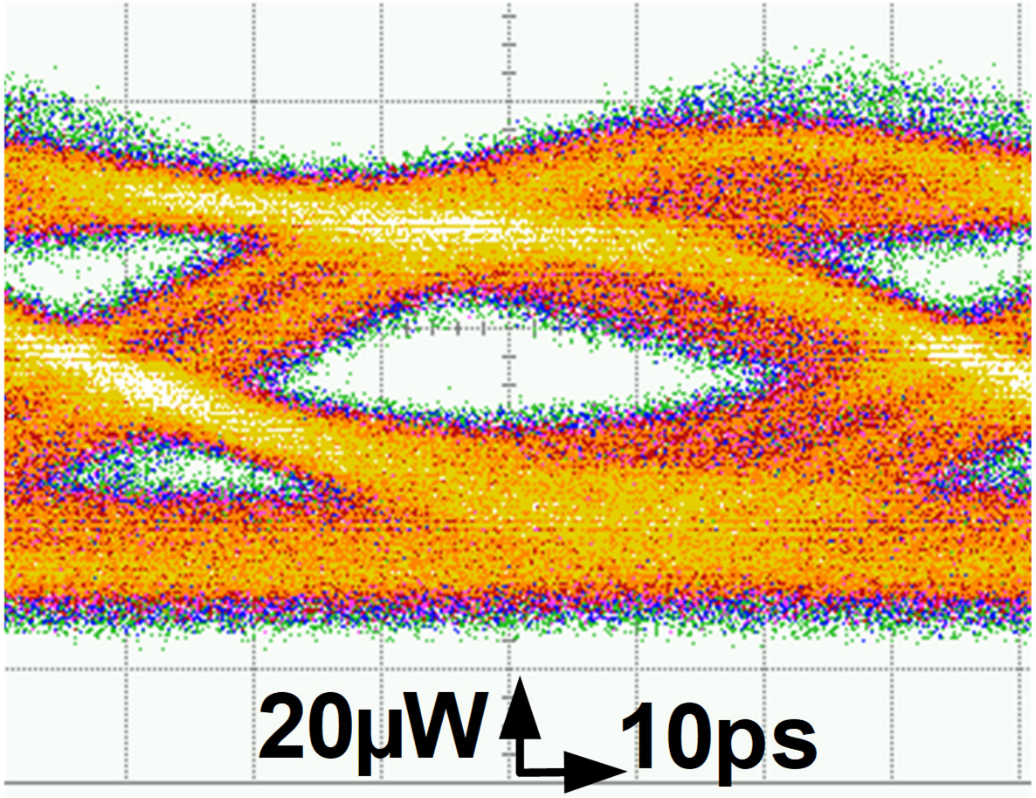
- No EQ
  - Overshooting and ringing on rising edge
  - Slow, unsettled falling edge
  - Reduce eye-opening



- Asymmetric EQ
  - Reduce overshooting
  - Faster falling edge
  - Increased eye-opening



14 Gb/s Eye Diagram



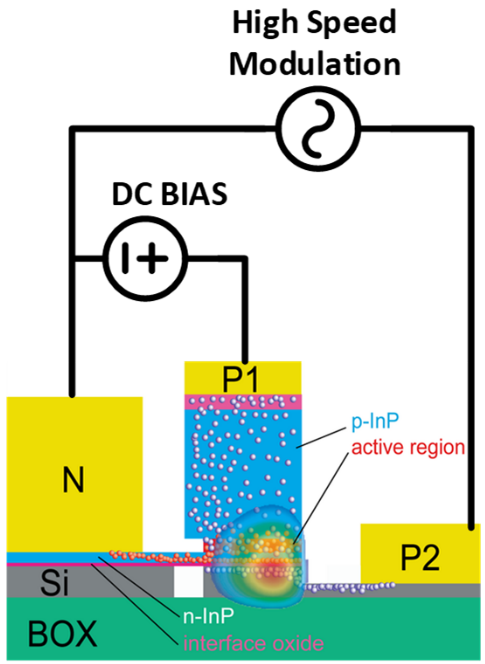
- 14Gb/s data-rate achieved with asymmetric FFE equalization
- 5.7dB of extinction ratio
- 144.5mW power consumption
  - 10.3pJ/b

Summary Table

Reference	[Ramaswamy OFC 2015]	[Chong MWSCAS 2015]	This work
Photonic Device	Fabry-Perot cavity laser + Electro absorption modulator	Microring Laser	Microring Laser
Data Rate Per Channel (Gb/s)	28	12.5	14
Number of Channels	4	1	5
Energy Efficiency (pJ/bit)	10	5.28	10.3
Integrated Driver	yes	no	yes

Hybrid Microring Laser Transmitter Summary

- A mutli-channel hybrid microring laser transmitter with integrated driver



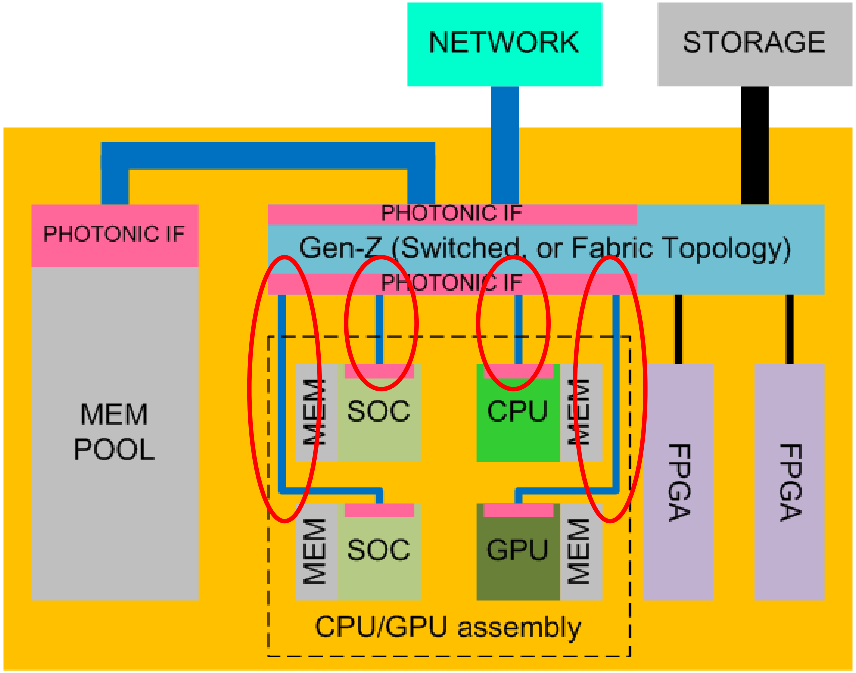
- MOS capacitor enables low power wavelength tuning
  - Can be used for direct modulation (on-going)
- Asymmetric FFE equalization utilized in driver to overcome non-linear microring dynamics
- 14Gb/s operation per channel is achieved
  - 70Gb/s per transmitter

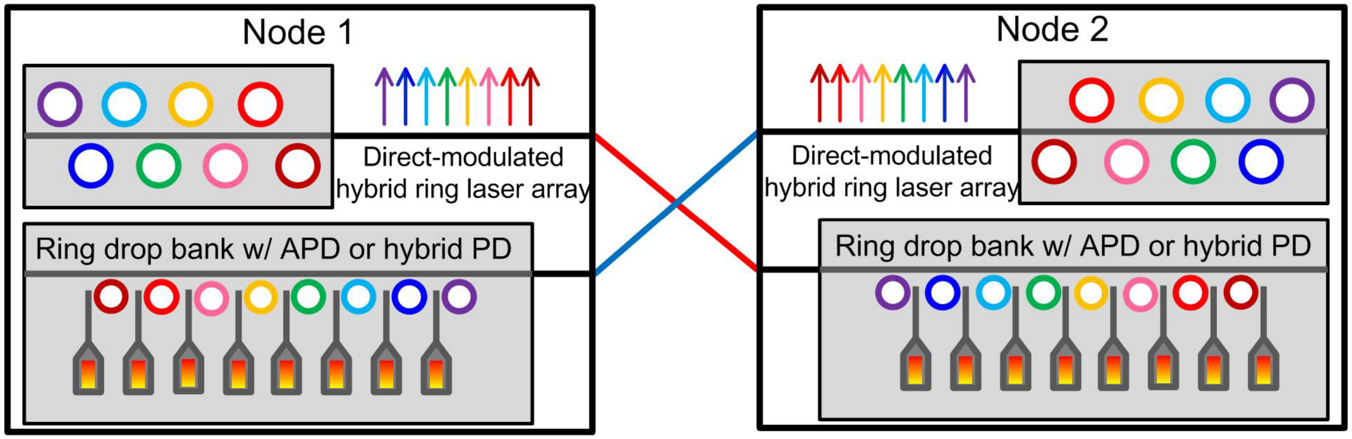
Agenda

- Fabry-Perot Lasers
- Distributed-Feedback (DFB) Lasers
- Hybrid Silicon Lasers
- Comb Lasers
- A 14 Gb/s Directly Modulated Hybrid Microring Laser Transmitter
- A Directly Modulated Quantum Dot Microring Laser Transmitter with Integrated CMOS Driver
- A 22Gb/s Directly Modulated Optical Injection-Locked Quantum-Dot Microring Laser Transmitter with Integrated CMOS Driver

Traffic Scenarios in HPCs

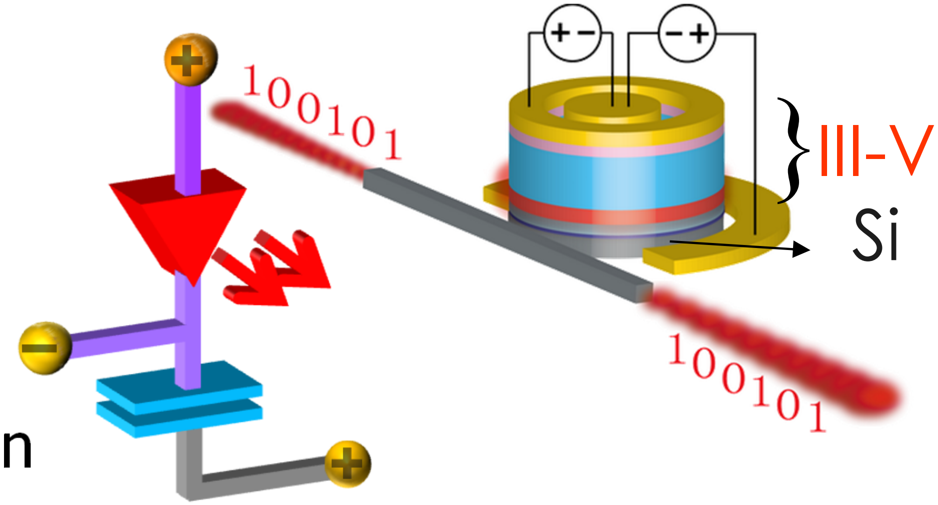
- Dynamic (G-T bps) data traffic common in high-performance computing
- Medium (x10 Gbps) traffic up to several meters reach requires flexible, compact and energy-efficient links

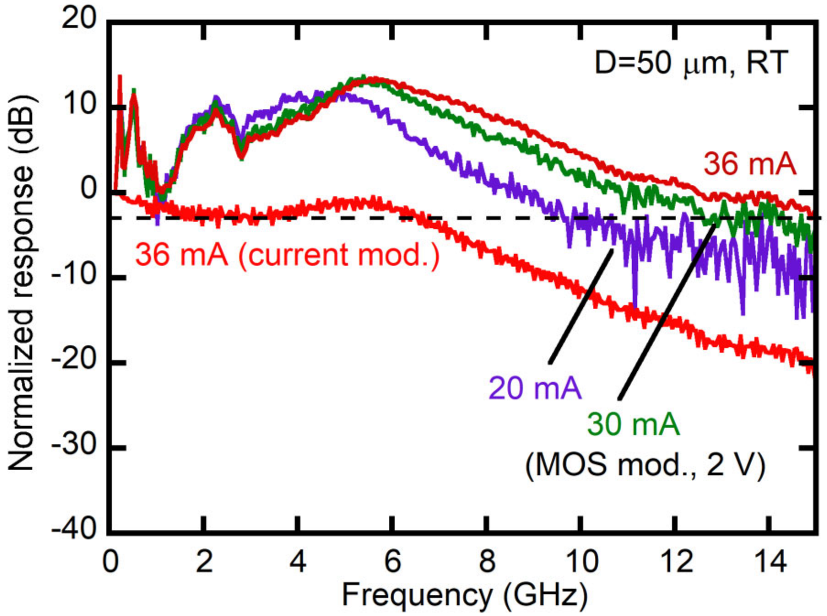


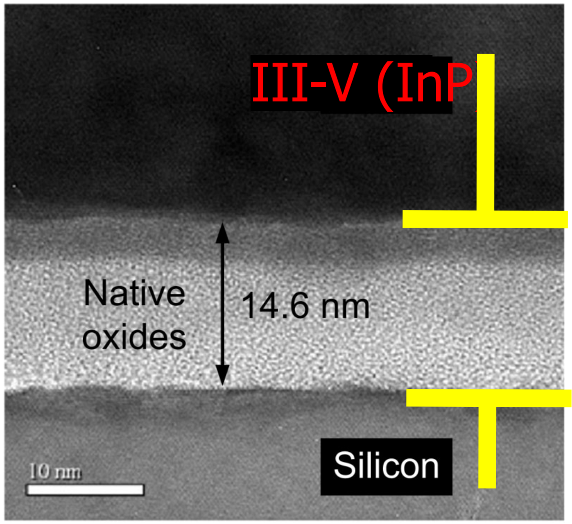


Hybrid Microring Lasers Array

- Laser source on silicon
  - On-chip dense integration
  - Compact laser cavity
    - Low threshold operation
    - Favor high-speed modulation
  - Mirror-free output coupling
  - Novel three-terminal design

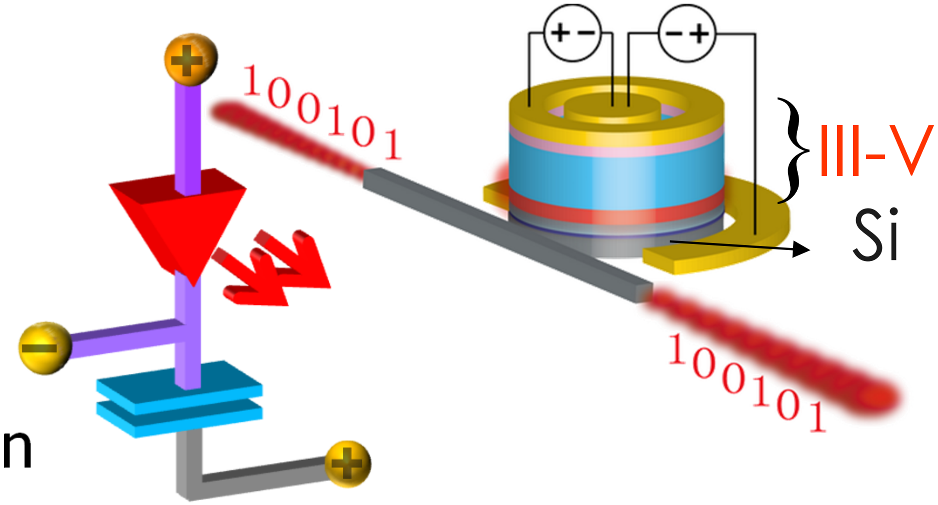


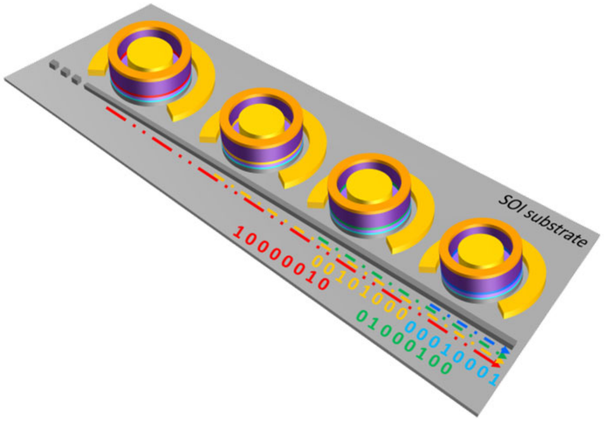


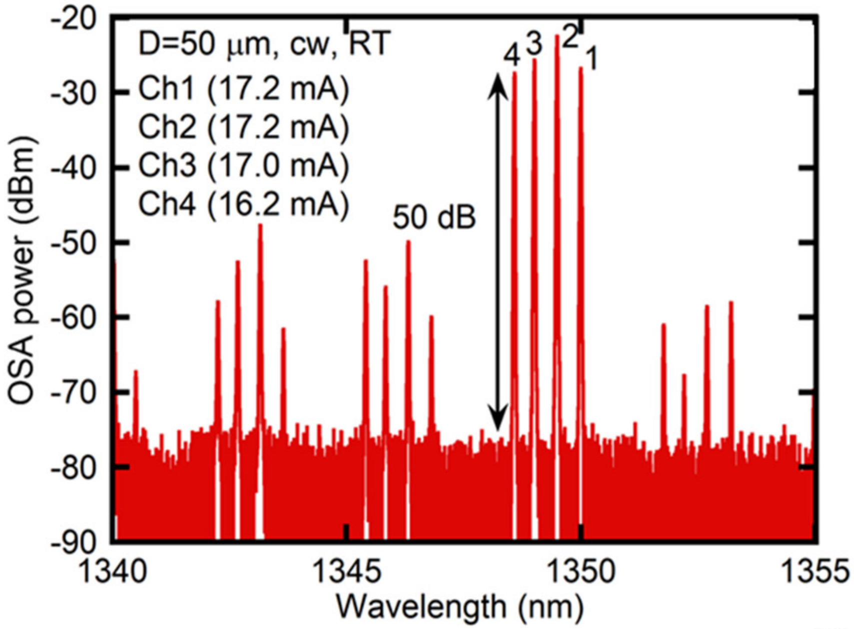


Hybrid Microring Lasers

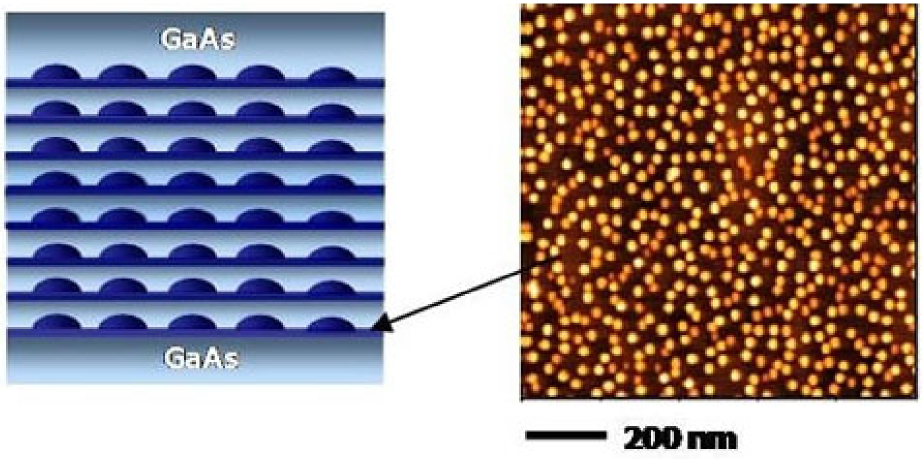
- Laser source on silicon
  - On-chip dense integration
  - Compact laser cavity
    - Low threshold operation
    - Favor high-speed modulation
  - Mirror-free output coupling
  - Novel three-terminal design
- Inherent WDM architecture



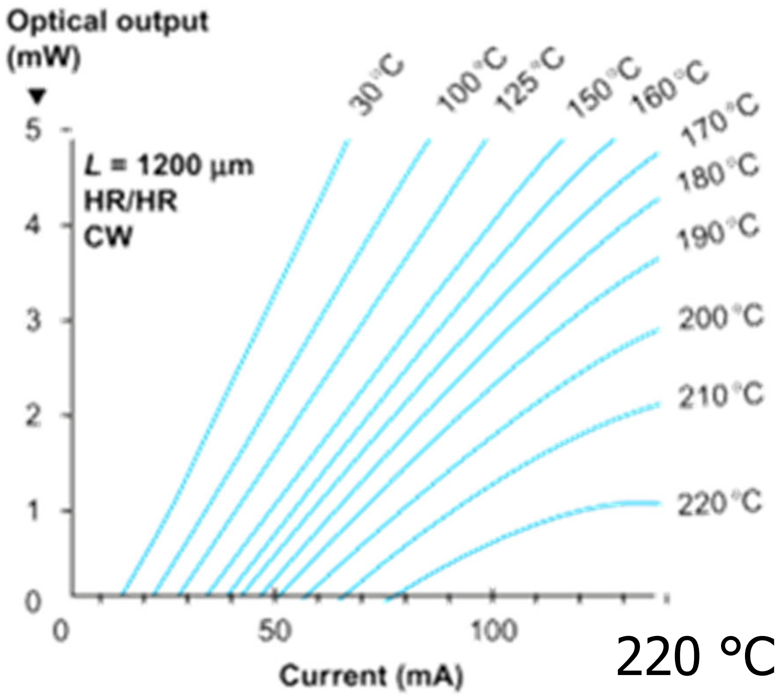




Quantum Dot Laser Gain Medium

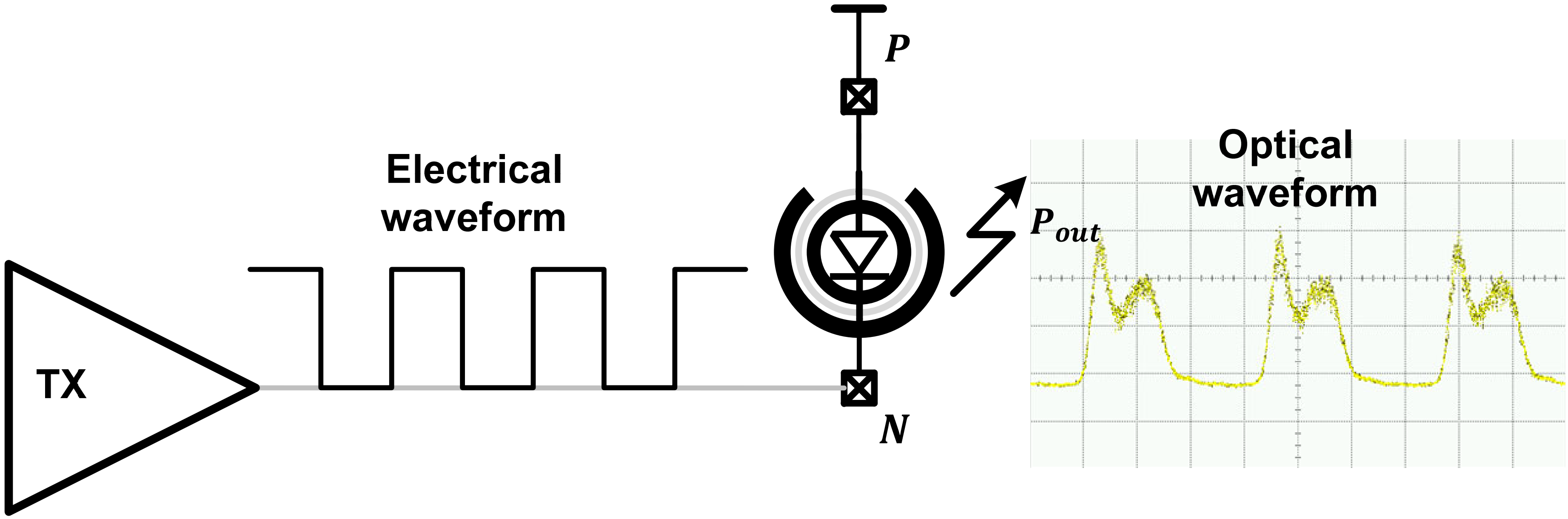


- High temperature operation
- Little sensitivity to temperature fluctuations
- Low threshold current density
- Wide gain bandwidth
- Low amplitude noise (RIN)
- Low sensitivity to external optical feedback



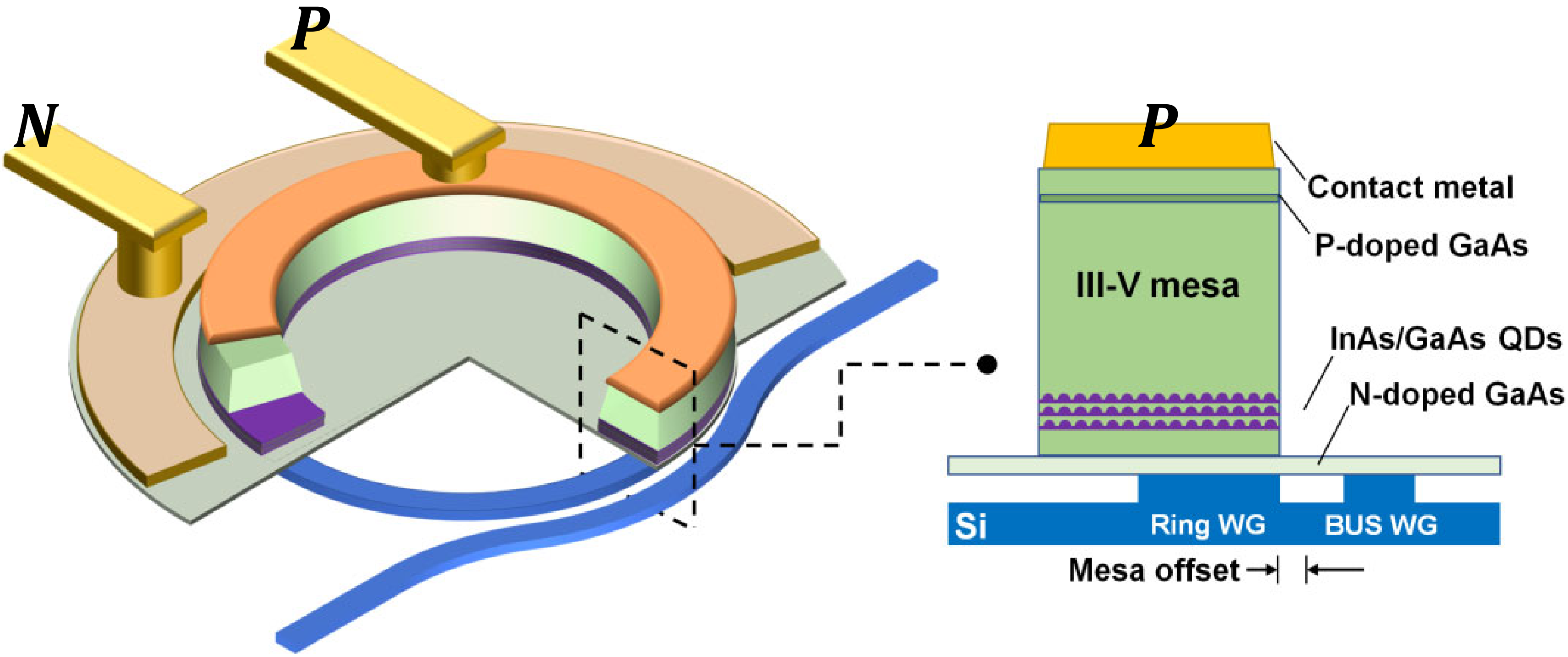
220 °C CW lasing: QD Laser Inc. (2011)

Microring Laser Model



- Microring laser model required for co-design of CMOS TX driver
  - Load impedance, current threshold, and voltage drop
  - Dynamic behavior

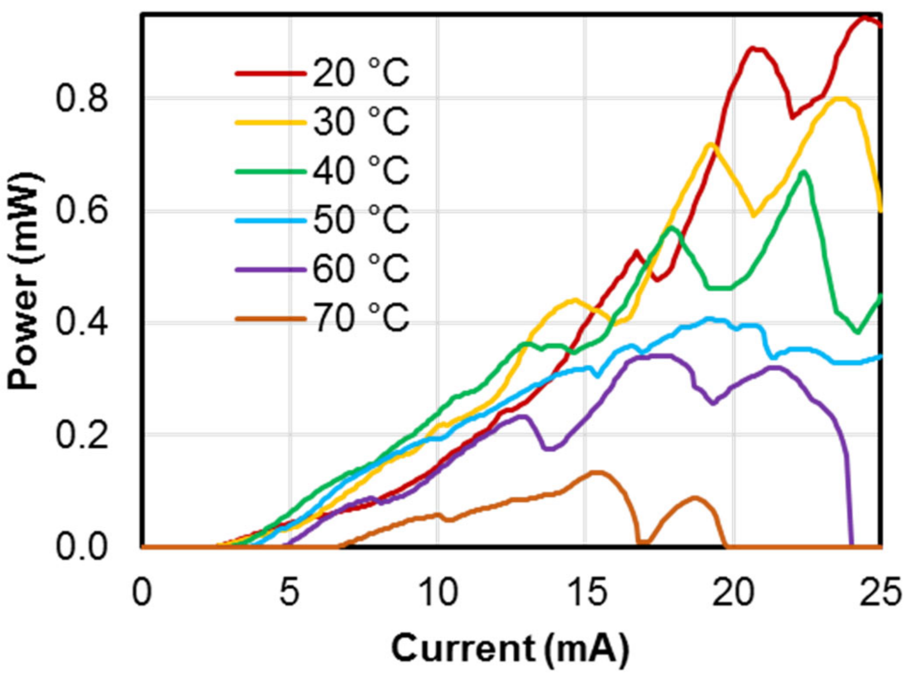
QD Microring Laser Design

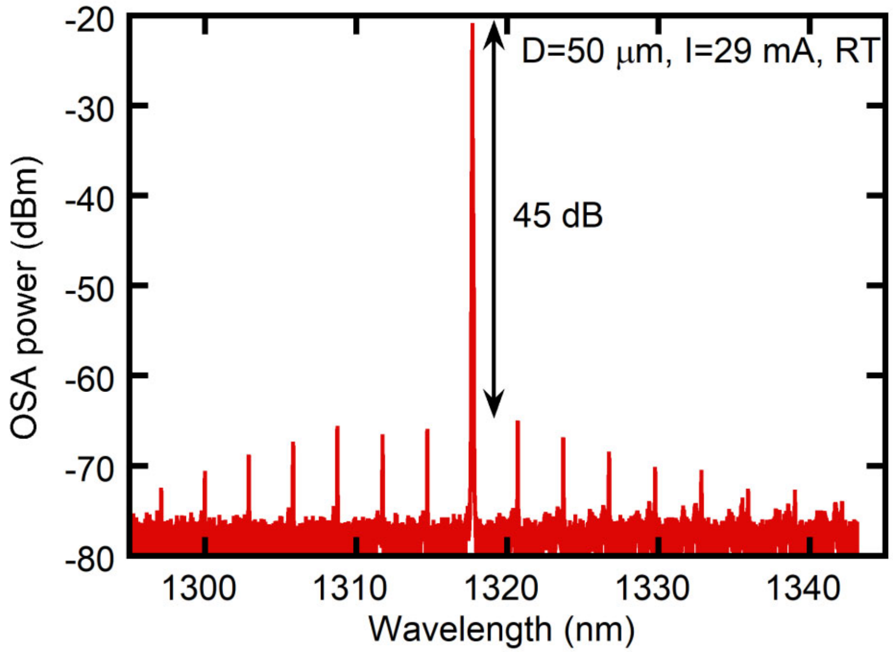


- Hybrid Quantum Dot (QD) Microring Laser
  - D=50 μm, 8-layer InAs QD active region (O-band)

- Structure is bonded on a SOI substrate with 400nm top silicon thickness

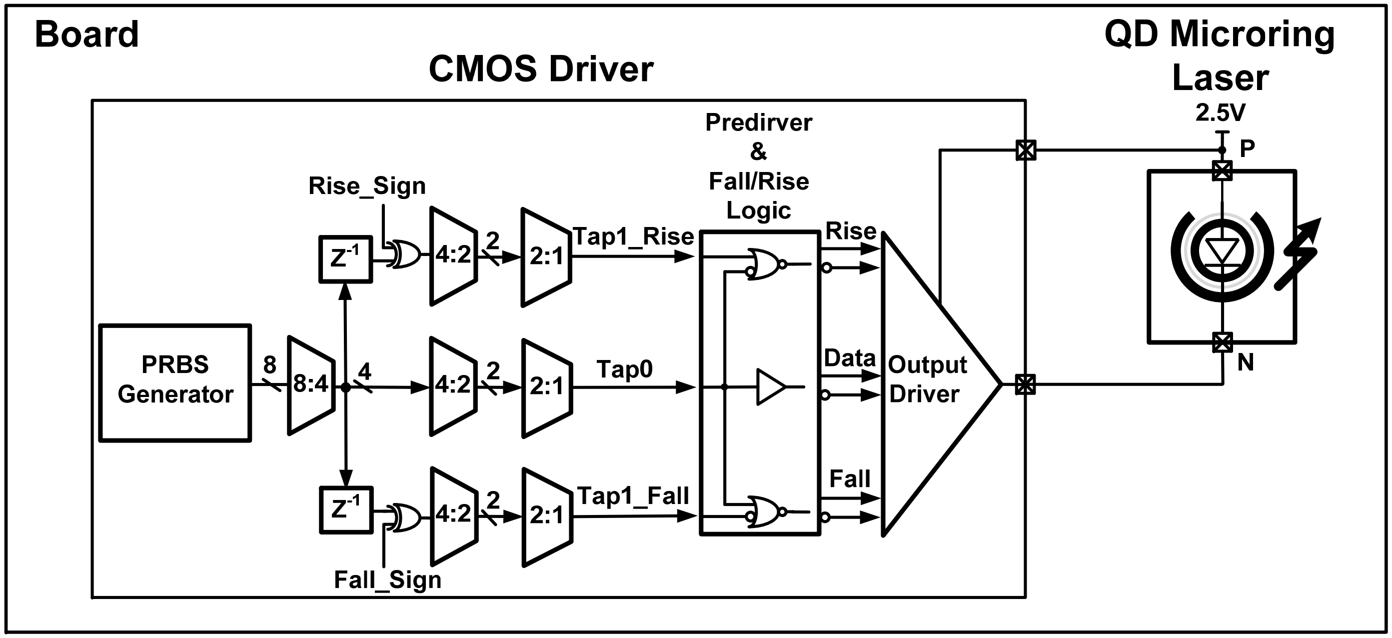
Device Static Performance



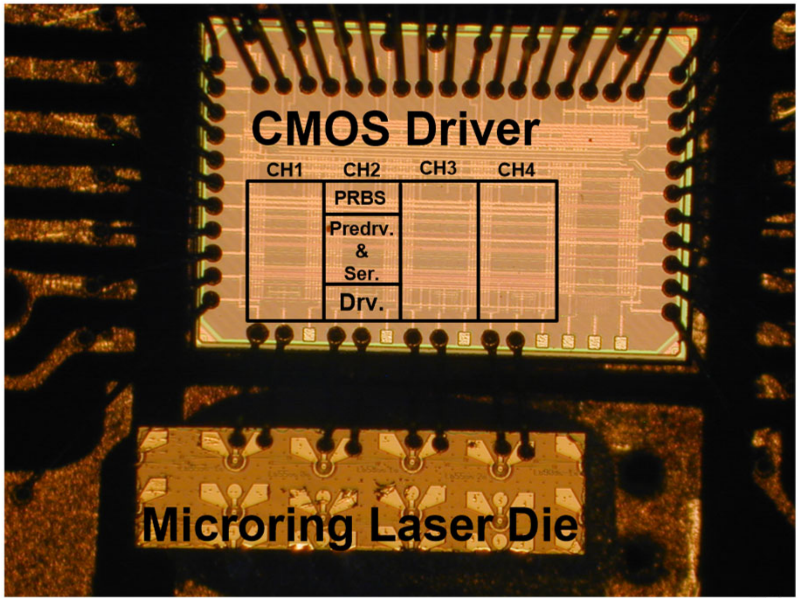


- Threshold current: ~1-3 mA (cw lasing)
- Robust cw operation up to 70 ^{o}C stage temperature
- Fiber coupled output power: up to -10 dBm (w/ 10 dB grating coupler loss)
- Single-mode spectrum at O-band
  - Extinction ratio >60 dB, Side-mode suppression ratio > 45 dB

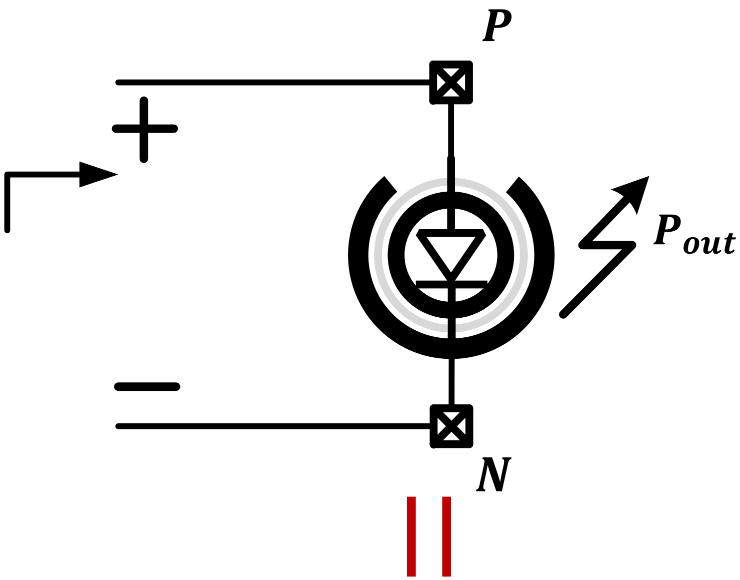
Microring Laser Model with Driver

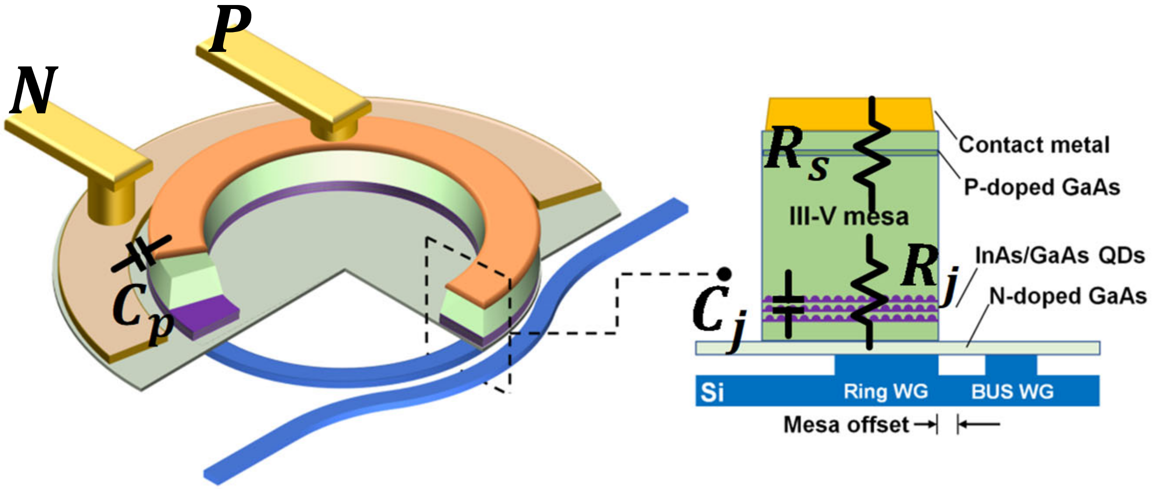


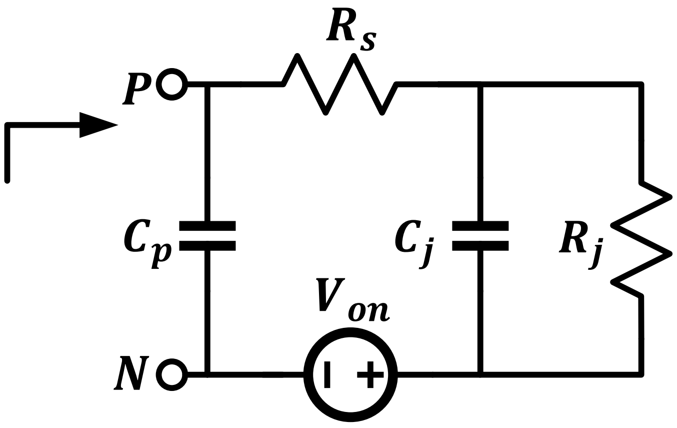
- Hybrid chip-on-board integration approach with CMOS driver die wirebonded to the QD Microring Laser die
- QD Microring Laser co-simulation model accurately captures interconnect and device parasitics and optical dynamics



Microring Laser Model (Electrical Part)



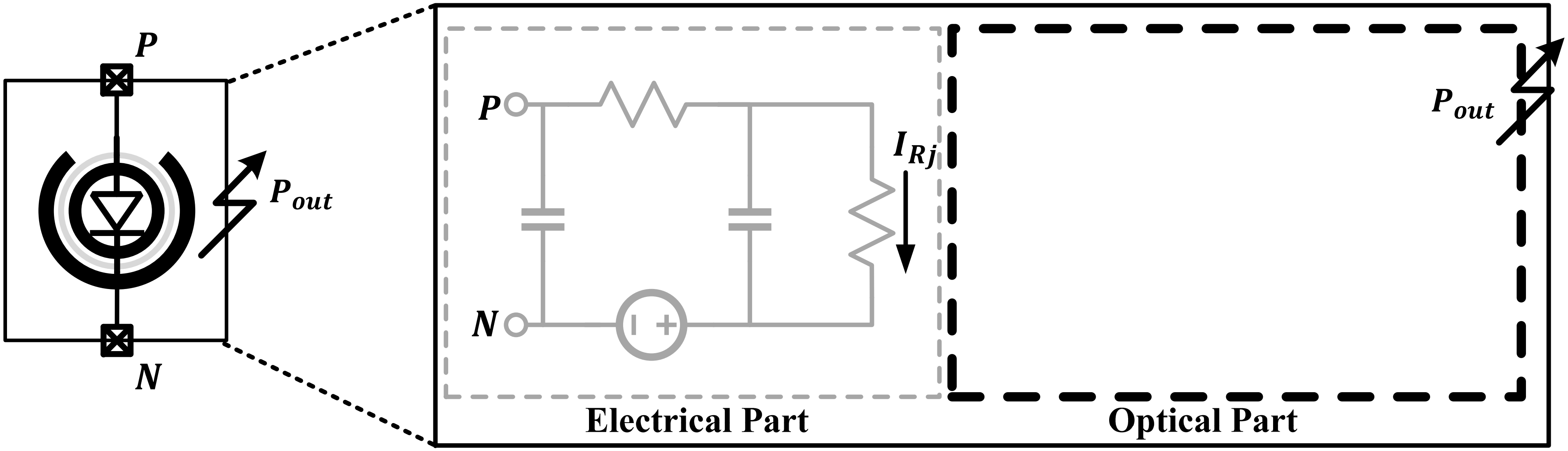




Electrical Part

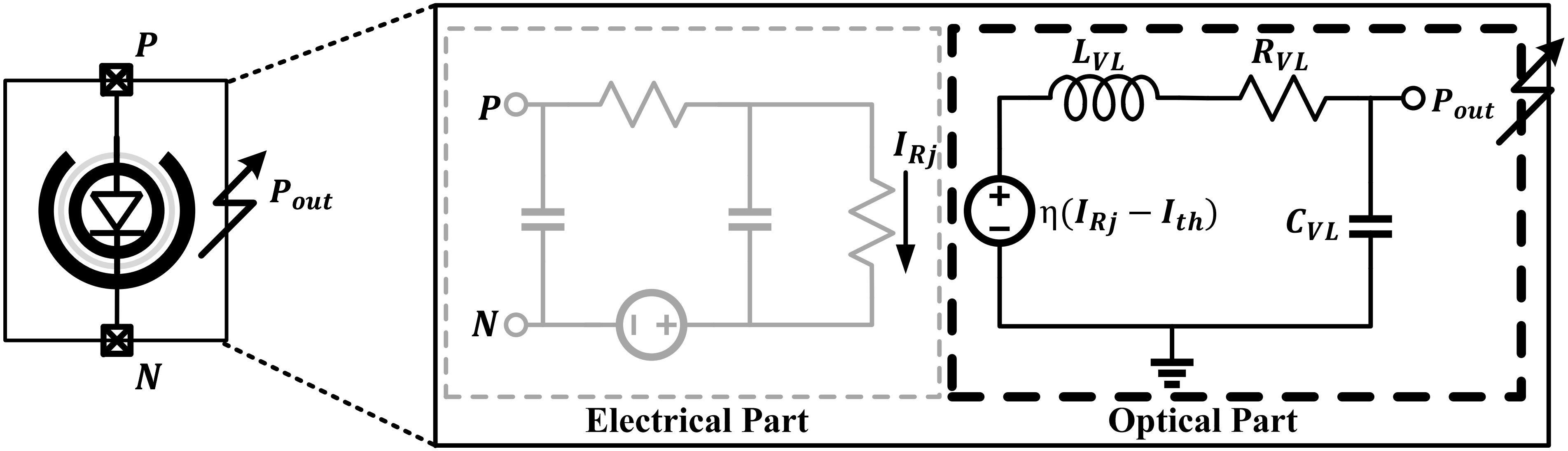
- Electrical part models laser diode characteristics
  - Turn-on voltage (V_{on})
  - Junction capacitance (C_j)
  - Junction resistance (R_j)
  - Series resistance (R_s)
  - Parasitic capacitance (C_p)

Microring Laser Model (Optical Part)



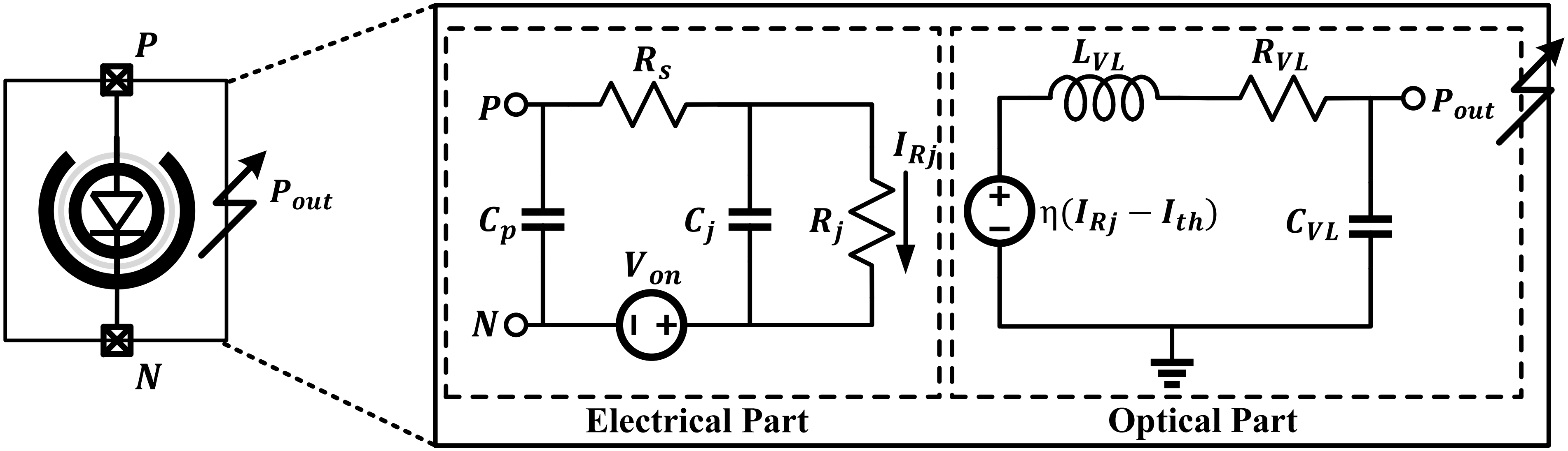
- Laser optical model
  - $H = \frac{P_{out}}{I_{Rj}} = const \times f_r^2/(f_r^2 - f^2 + j\left(\frac{f}{2\pi}\right)\gamma)$
    → 2^{nd} order low-pass with peaking
  - $f_r = D\sqrt{I_{Rj} - I_{th}}$
    → Resonance frequency $f_r \propto \sqrt{I_{Rj} - I_{th}}$
  - $\gamma = K f_r^2 + \gamma_0$
    → Damping factor $\gamma \propto {f_r}^2 \propto (I_{\mathrm{Rj}} - I_{th})$

Microring Laser Model (Optical Part)



- Equivalent circuit model
  - Voltage source $= \eta\left(I_{Rj} - I_{th}\right)$
  - RLC models the 2-order low-pass network with peaking
  - R & L are current-dependent
    - $L_{VL} = 1/\{4\pi^2 C_{VL} D^2 (I_{Rj} - I_{th})\}$
    - $R_{VL} = (K f_r{}^2 + \gamma_0) L_{VL}$

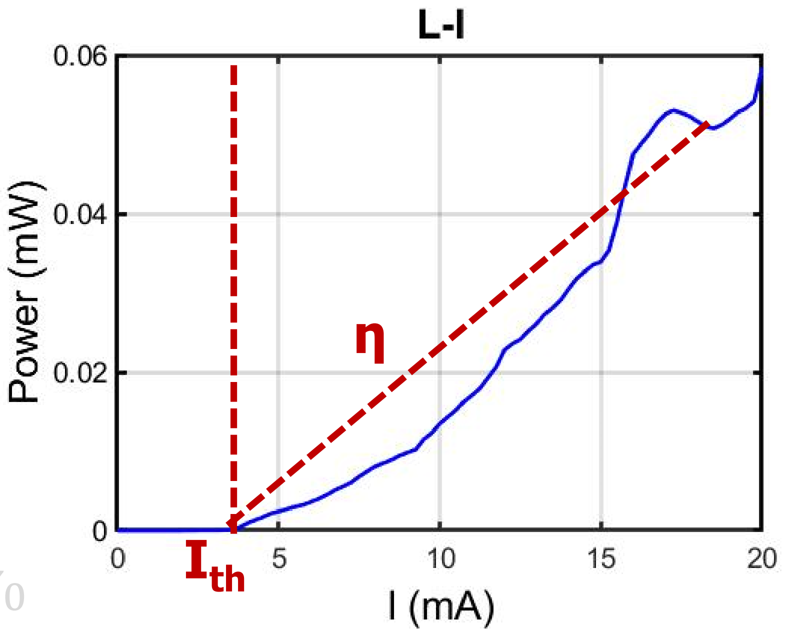
Microring Laser Model

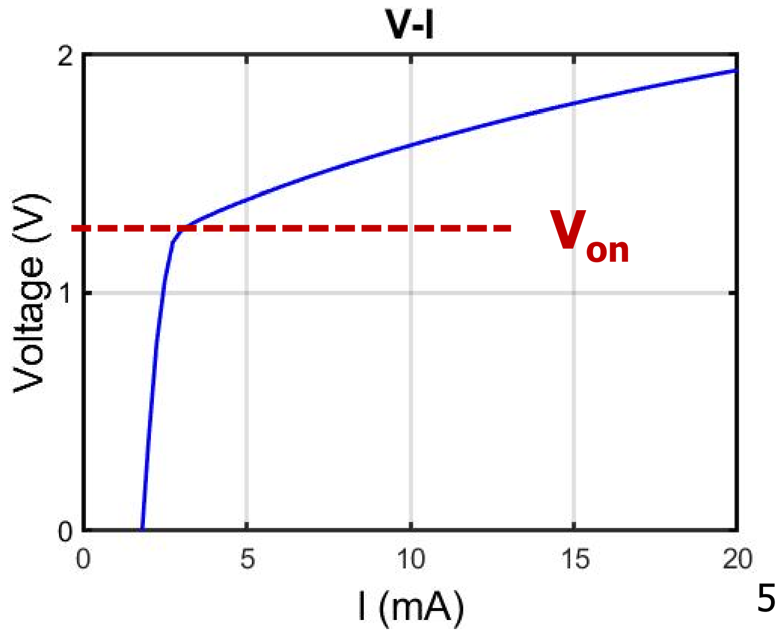


- Implemented in VerilogA
- 10 parameters
  - Electrical part: C_j, R_j, R_s, C_p, V_{on}
  - Optical part: I_{th}, η, D-factor, K-factor, γ_0

Parameter Extraction Process

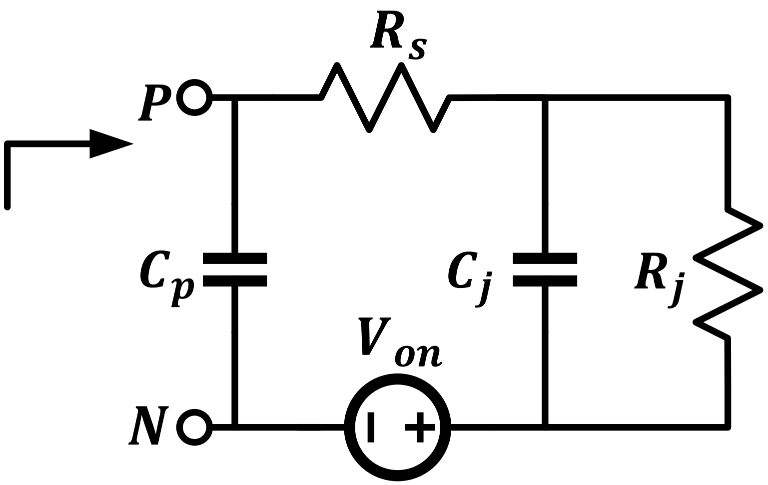
1. Light power versus I → I_{th} and η
2. Voltage versus I → V_{on}
3. S_{11} curve fitting → C_p, R_s, C_j, R_j
   - $S_{11} = \frac{Z_{in}-50}{Z_{in}+50}$
   - $Z_{in} = \frac{R_s+sC_jR_jR_s+R_j}{1+sC_jR_j+sC_pR_s+sR_jC_p+s^2C_sR_jC_pR_s}$
4. S_{21} curve fitting → D-factor, K-factor, γ_0
   - $S_{21} = \frac{I_{Rj}}{V_{in}} * \frac{P_{out}}{I_{Rj}}$
   - $\frac{I_{Rj}}{V_{in}} = \frac{1}{R_s+R_j+sC_jR_jR_s}$
   - $H = \frac{P_{out}}{I_{Rj}} = const \times \frac{f_r^2}{f_r^2-f^2+j\left(\frac{f}{2\pi}\right)\gamma}$
   - $f_r = D\sqrt{I_{Rj}-I_{th}}$
   - $\gamma = Kf_r^2+\gamma_0$





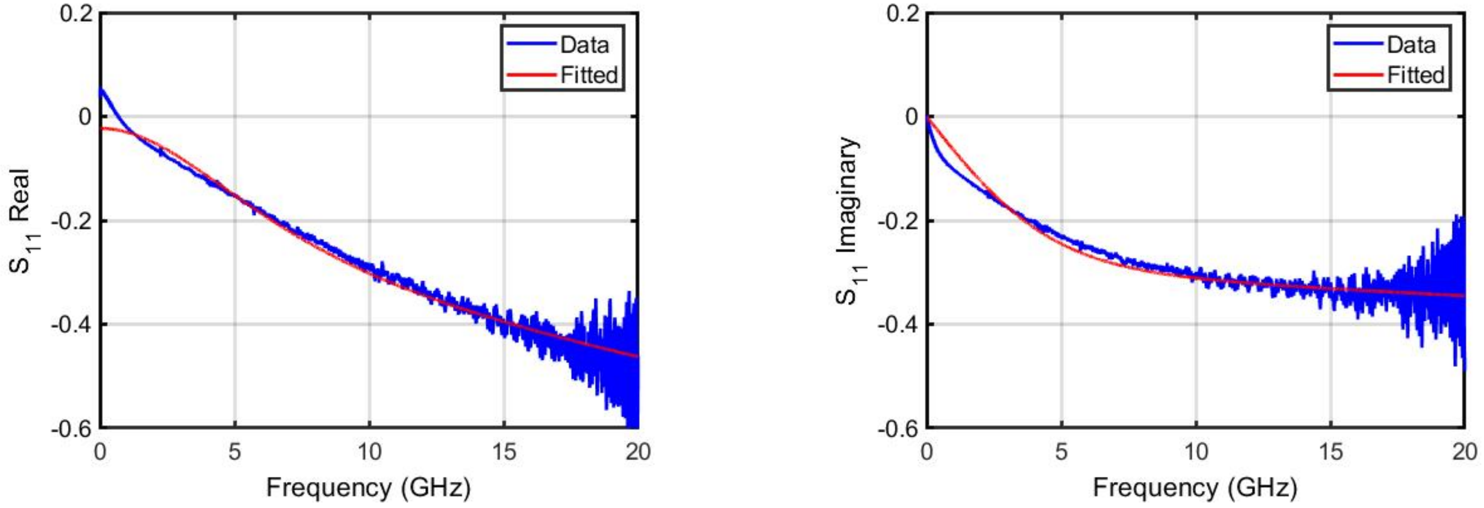
Parameter Extraction Process

1. Light power versus I → I_{th} and η
2. Voltage vesus I→ V_{th}
3. S_{11} curve fitting→ C_p, R_s, C_j, R_j
   - $S_{11} = \frac{Z_{in}-50}{Z_{in}+50}$
   - $Z_{in} = \frac{R_s+sC_jR_jR_s+R_j}{1+sC_jR_j+sC_pR_s+sR_jC_p+s^2C_sR_jC_pR_s}$

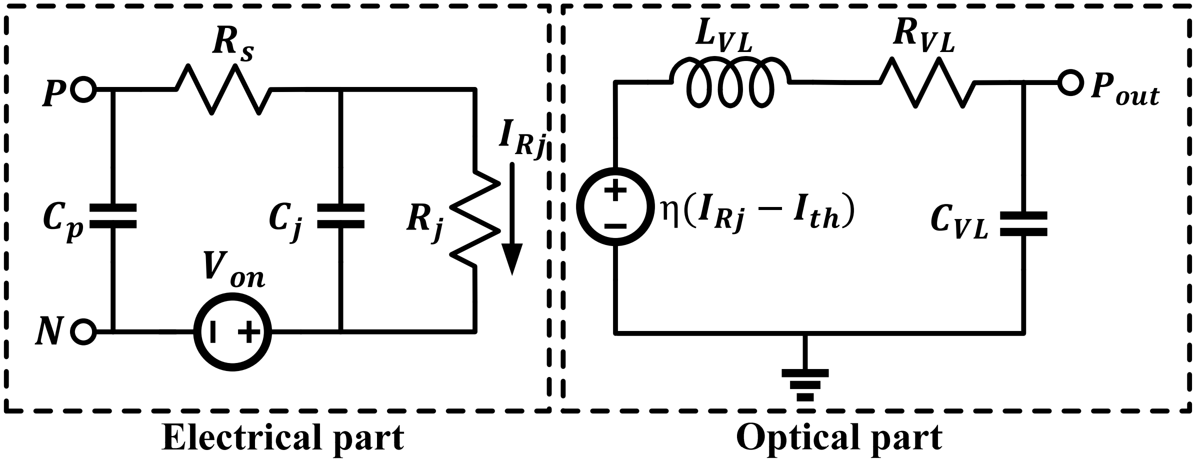


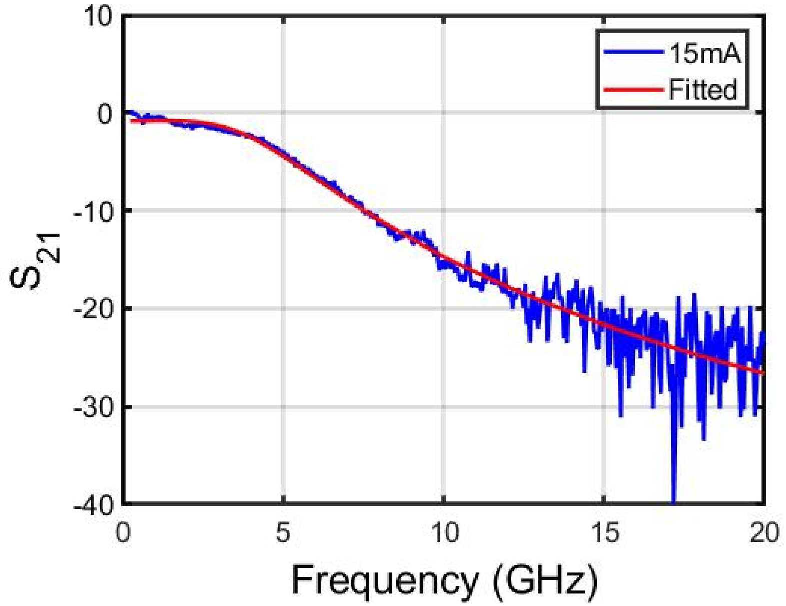
Electrical Part

I_{Ri}=10mA

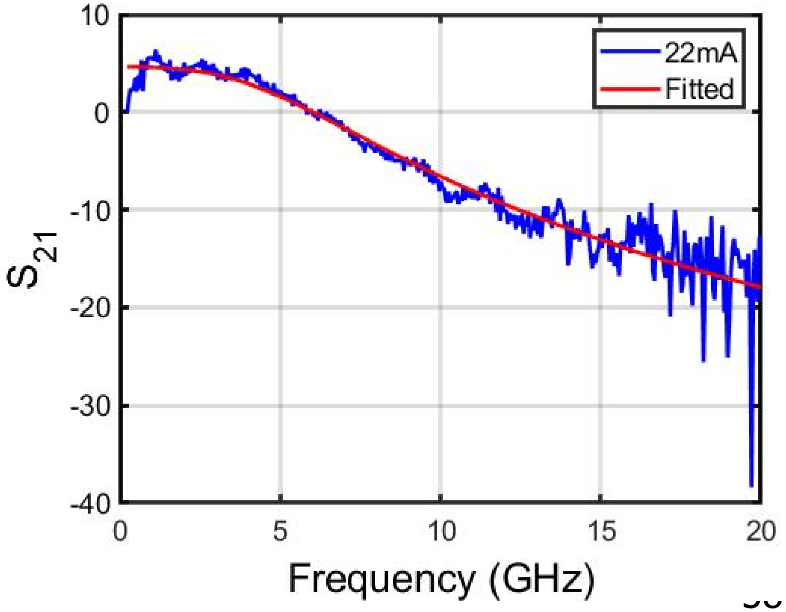


Parameter Extraction Process



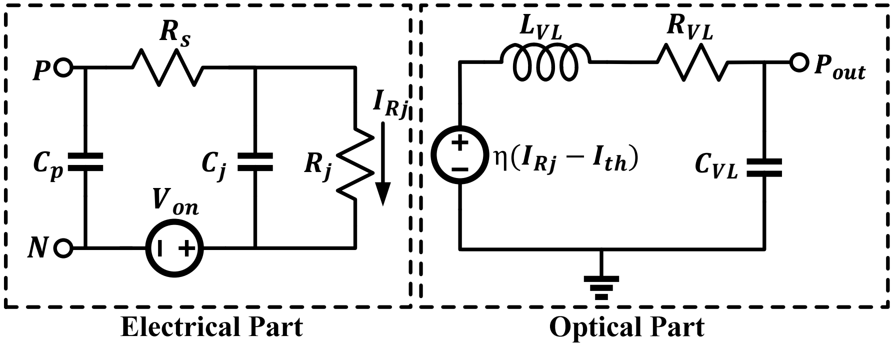


4. S_{21} curve fitting → D-factor, K-factor, γ_0
   - $S_{21} = \frac{I_{Rj}}{V_{in}} * \frac{P_{out}}{I_{Rj}}$
   - $\frac{I_{Rj}}{V_{in}} = \frac{1}{R_s + R_j + sC_jR_jR_s}$
   - $H = \frac{P_{out}}{I_{Rj}} = const \times f_r^2/(f_r^2 - f^2 + j\left(\frac{f}{2\pi}\right)\gamma)$
   - $f_r = D\sqrt{I_{Rj} - I_{th}}$
   - $\gamma = K f_r^2 + \gamma_0$



Parameter Extraction Process

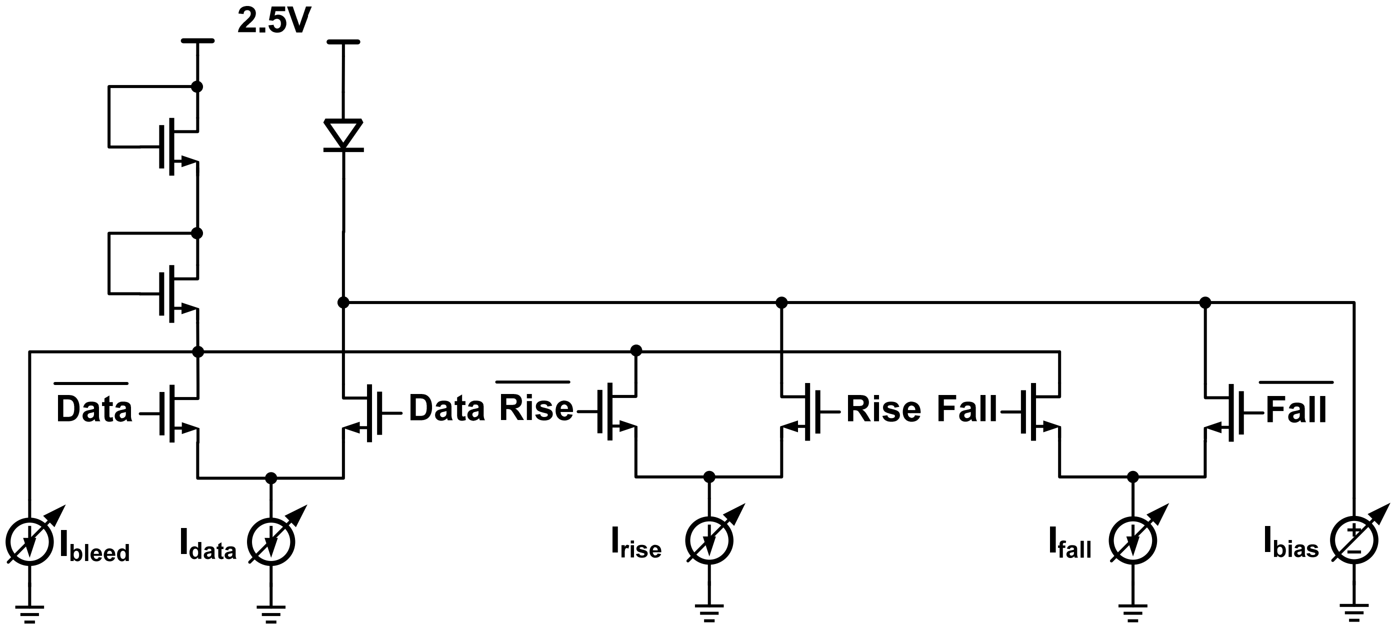
1. Light power versus I → I_{th} and η
2. Voltage versus I→ V_{th}
3. S_{11} curve fitting→ C_p, R_s, C_j, R_j
   - $S_{11} = \frac{Z_{in}-50}{Z_{in}+50}$
   - $Z_{in} = \frac{R_s+sC_jR_jR_s+R_j}{1+sC_jR_j+sC_pR_s+sR_jC_p+s^2C_sR_jC_pR_s}$
4. S_{21} curve fitting → D-factor, K-factor, γ_0
   - $S_{21} = \frac{I_{Rj}}{V_{in}} * \frac{P_{out}}{I_{Rj}}$
   - $\frac{I_{Rj}}{V_{in}} = \frac{1}{R_s+R_j+sC_jR_jR_s}$
   - $H = \frac{P_{out}}{I_{Rj}} = const \times f_r^2/(f_r^2 - f^2 + j\left(\frac{f}{2\pi}\right)\gamma)$
   - $f_r = D\sqrt{I_{Rj} - I_{th}}$
   - $\gamma = Kf_r^2 + \gamma_0$



Electrical Parameters	Value
Junction Capacitance (C_j)	1200fF
Junction Resistance (R_j)	20.27Ω
Serial Resistance (R_s)	27.38Ω
Parasitic Capacitance (C_p)	217fF
Turn-on Voltage (V_{on})	1.2V

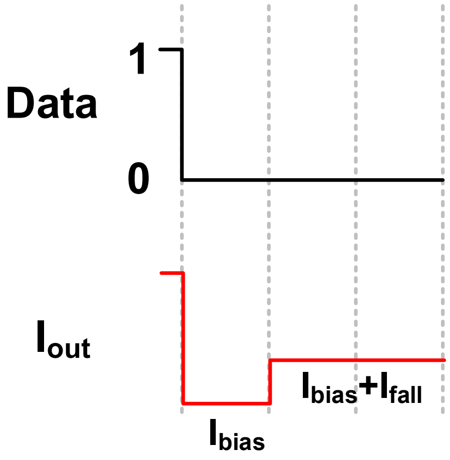
Optical Parameters	Value
Threshold current (I_{th})	4mA
Slope efficiency (η)	26.1uW/mA
D-factor (D)	1.09GHz/mA$^{0.5}$
K-factor (K)	1.53ns
Dampling factor offset(γ_0)	7.24ns^{-1}

Output Driver

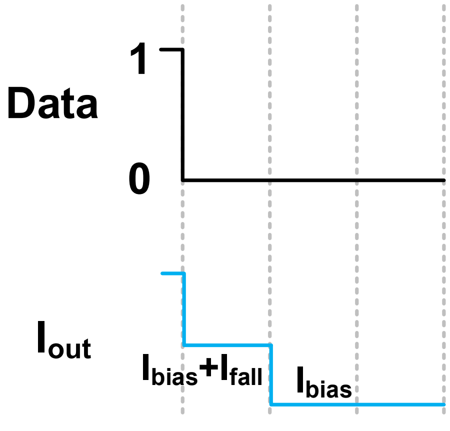


- I_{bias}: Controls laser bandwidth
- I_{data}: Controls current swing
- I_{fall}: Reduce/increase current on data fall depending on tap sign (FFE)
- I_{rise}: Reduce/increase current on data rise depending on tap sign (FFE)
- I_{bleed}: Provides biasing for the replica

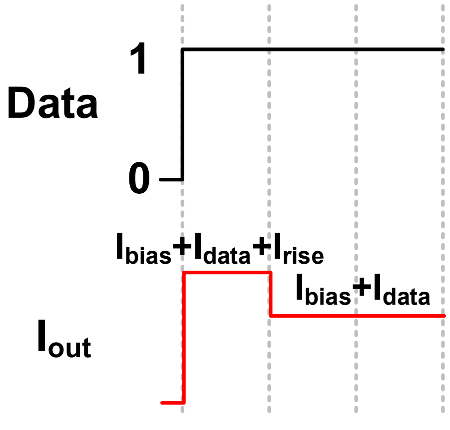
Asymmetric 2-tap Equalization



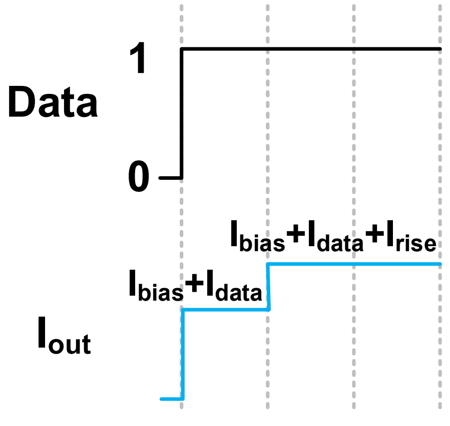
Falling edge
High-pass



Falling edge
Low-pass



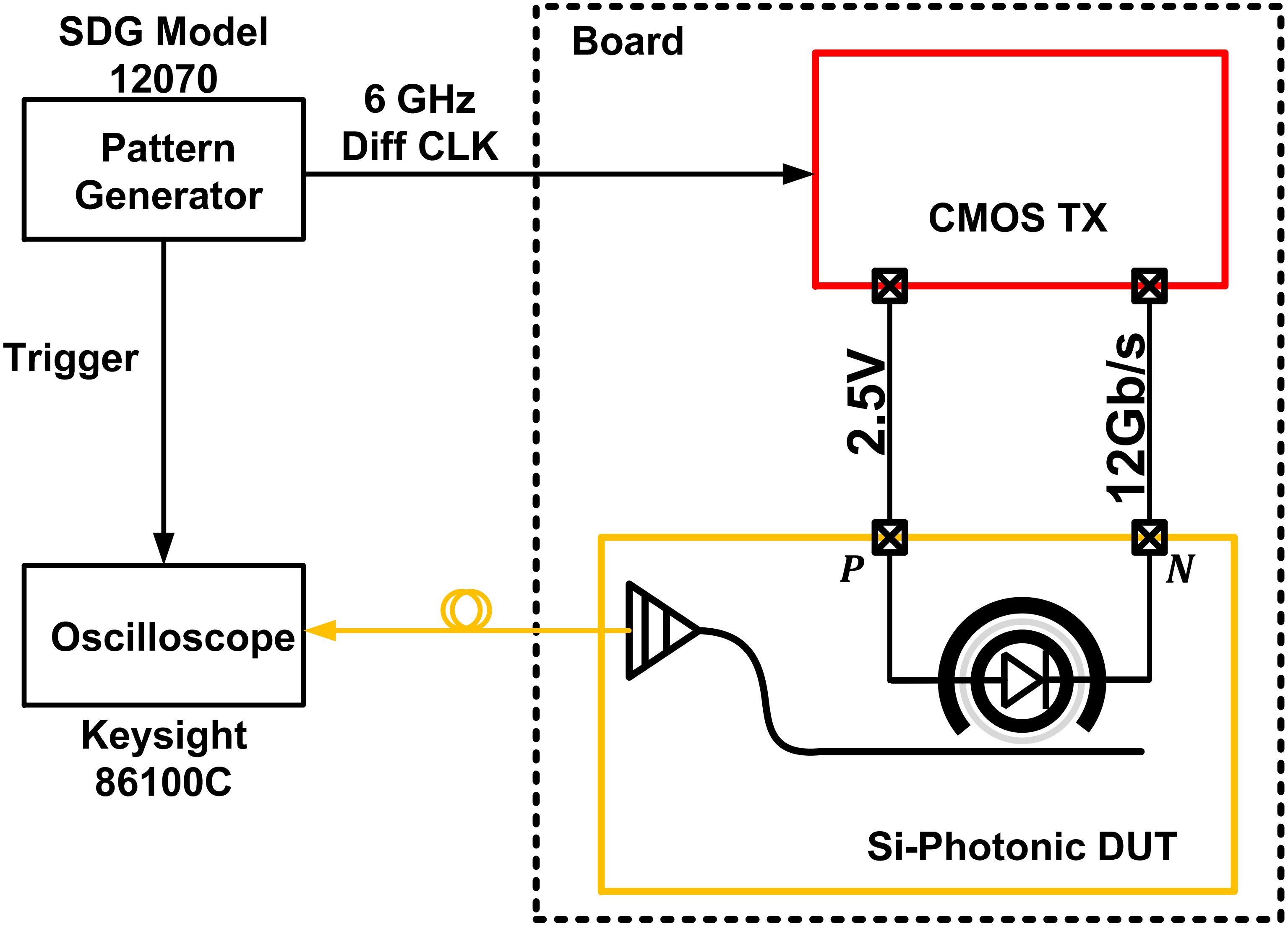
Rising edge
High-pass



Rising edge
Low-pass

- Rising edge and falling edge are equalized separately
- This provides flexibility to compensate both linear and non-linear responses

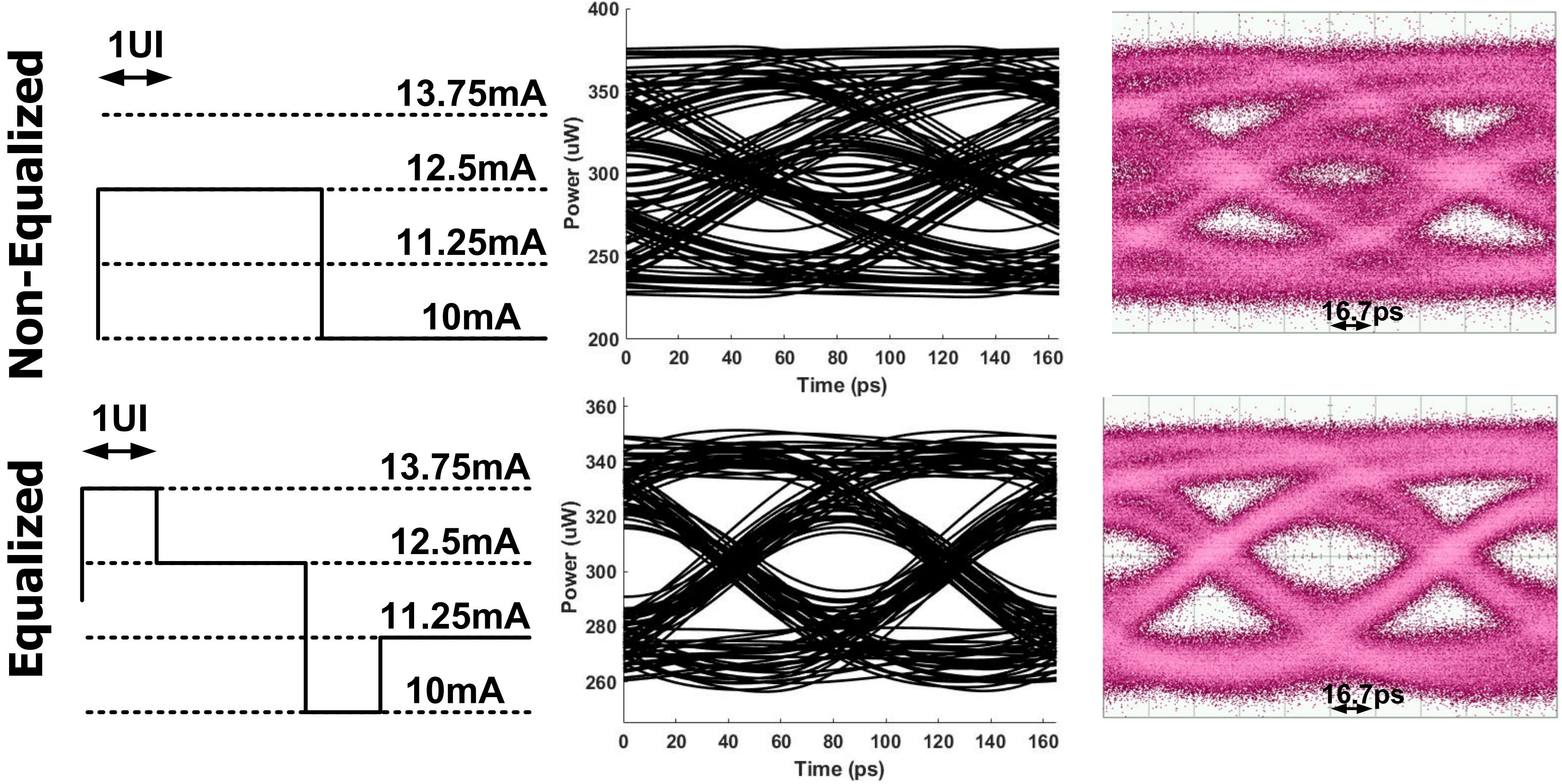
Test Setup


SDG Model
12070
Pattern Generator
6 GHz
Diff CLK
Board
CMOS TX
Trigger
2.5V
12Gb/s
P
N
Oscilloscope
Keysight
86100C
Si-Photonic DUT

12Gb/s Simulation and Measurement

Optical Eye Diagrams

Current Settings **Simulation** **Measurement**



- The first QD Microring Laser directly modulated with a CMOS driver
- The model well captures the photonic high-speed dynamics

Summary Table

Reference	**[Xu MWSCAS 2015]**	**[Roshan-Zamir OFC 2018]**	**This Work**
Photonic Device	Microring Laser	Quantum Well Microring Laser	Quantum Dot Microring Laser
Data Rate per Channel (Gb/s)	12.5	14	12
Number of Channels	1	5	4
Energy Efficiency (pJ/bit)	5.28	10.3	10.8
Integrated Driver	no	yes	yes

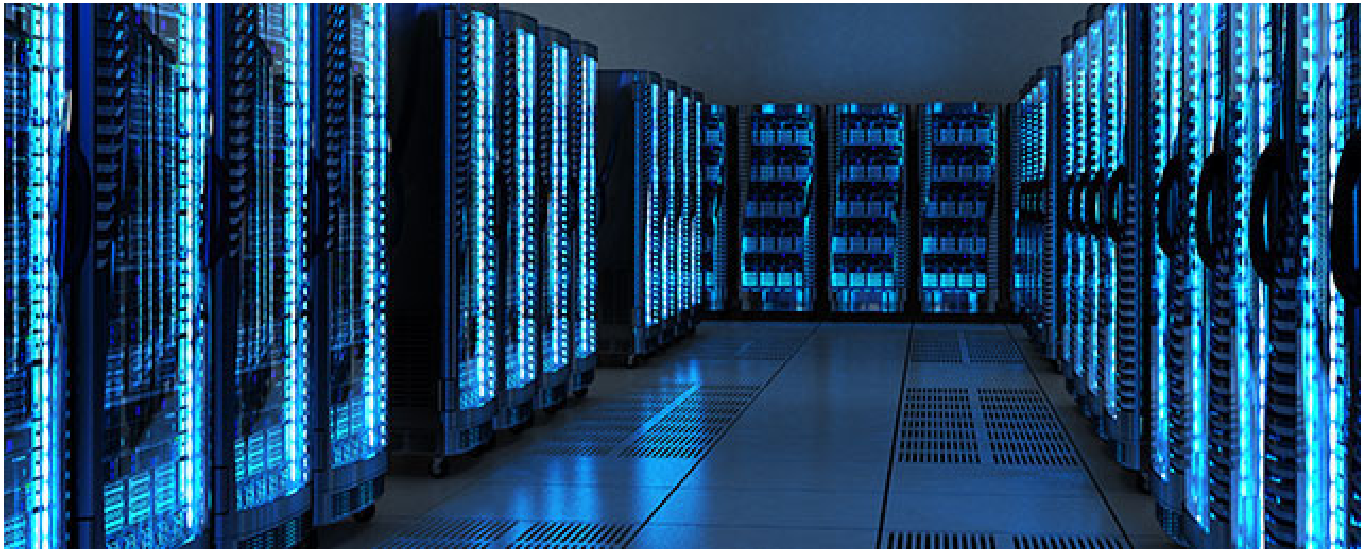
Quantum Dot Microring Laser Transmitter Summary

- The first hybrid-integrated directly-modulated QD microring laser system
- A QD microring laser model accurately captures the photonic high-speed dynamics
- This model allows for the co-design of an advanced CMOS transmitter with 2-tap asymmetric FFE that achieves 12Gb/s operation

Agenda

- Fabry-Perot Lasers
- Distributed-Feedback (DFB) Lasers
- Hybrid Silicon Lasers
- Comb Lasers
- A 14 Gb/s Directly Modulated Hybrid Microring Laser Transmitter
- A Directly Modulated Quantum Dot Microring Laser Transmitter with Integrated CMOS Driver
- A 22Gb/s Directly Modulated Optical Injection-Locked Quantum-Dot Microring Laser Transmitter with Integrated CMOS Driver

Motivation

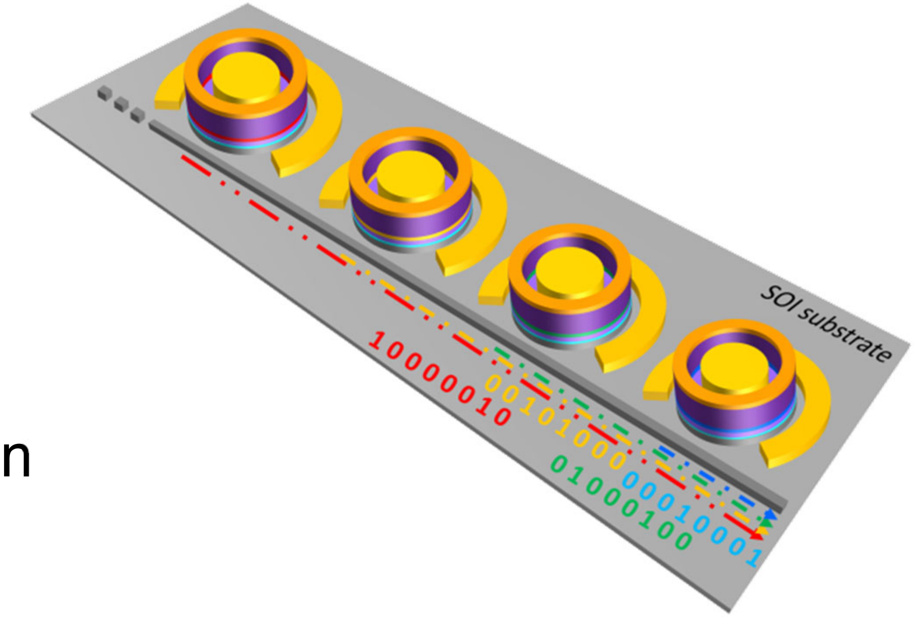


https://www.ntscom.com/enterprise-business/products/managed-services/virtual-cloud-servers

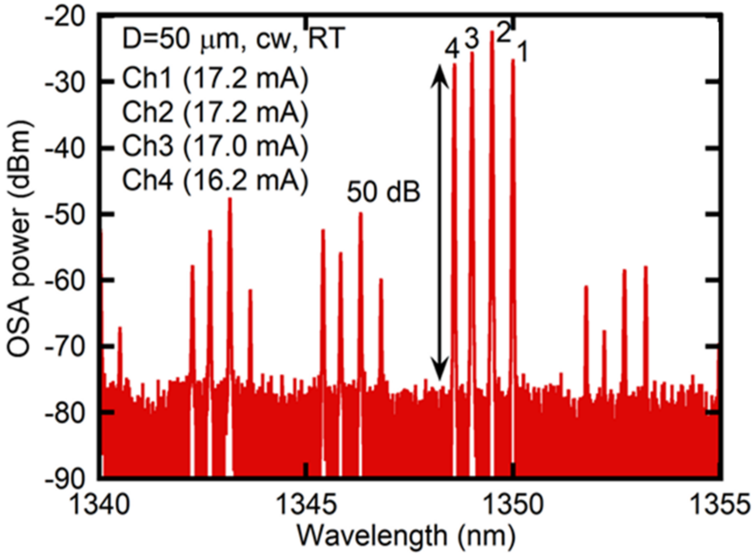
- 400Gb/s data center and high-performance computing
- Attractive integrated photonics solution
    - Remove channel limitation
    - High data density with wavelength-division multiplexing (WDM)

Hybrid Microring Lasers Array

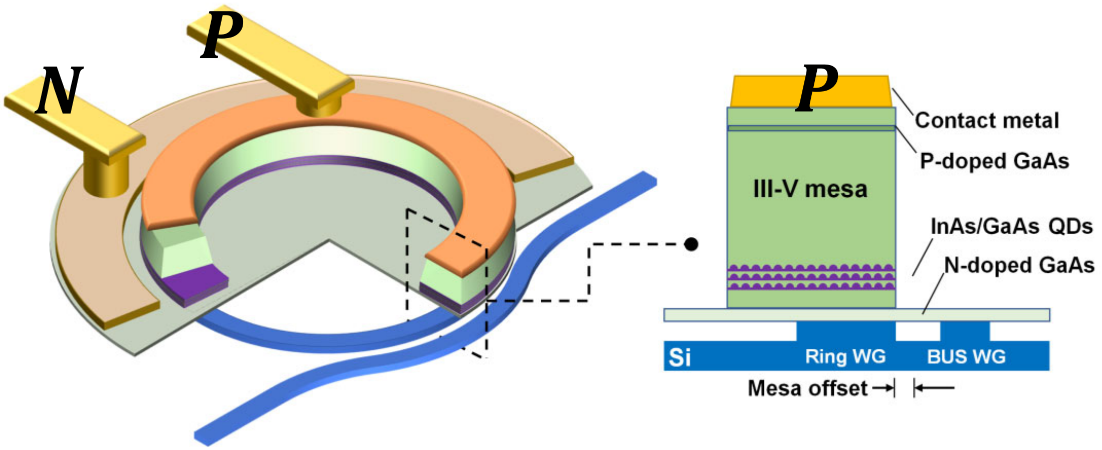
- Laser source on silicon
  - On-chip dense integration
  - Compact laser cavity
    - Low threshold operation
    - Favor high-speed modulation

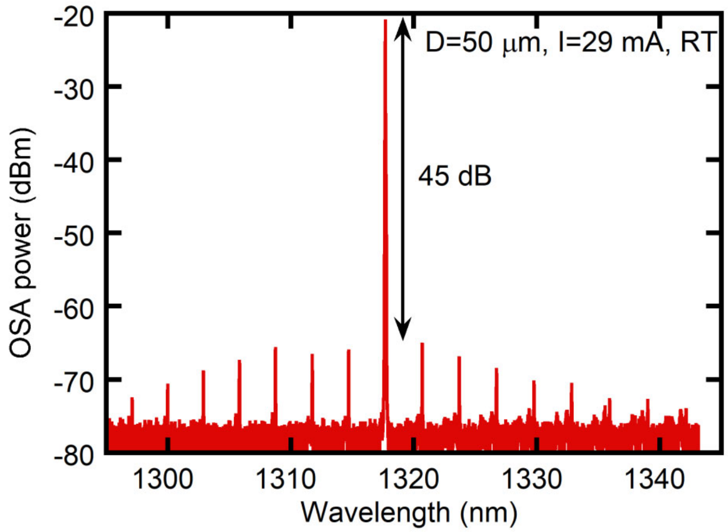


- Inherent WDM architecture
- Wavelength is set by the laser cavity dimension and current/voltage bias



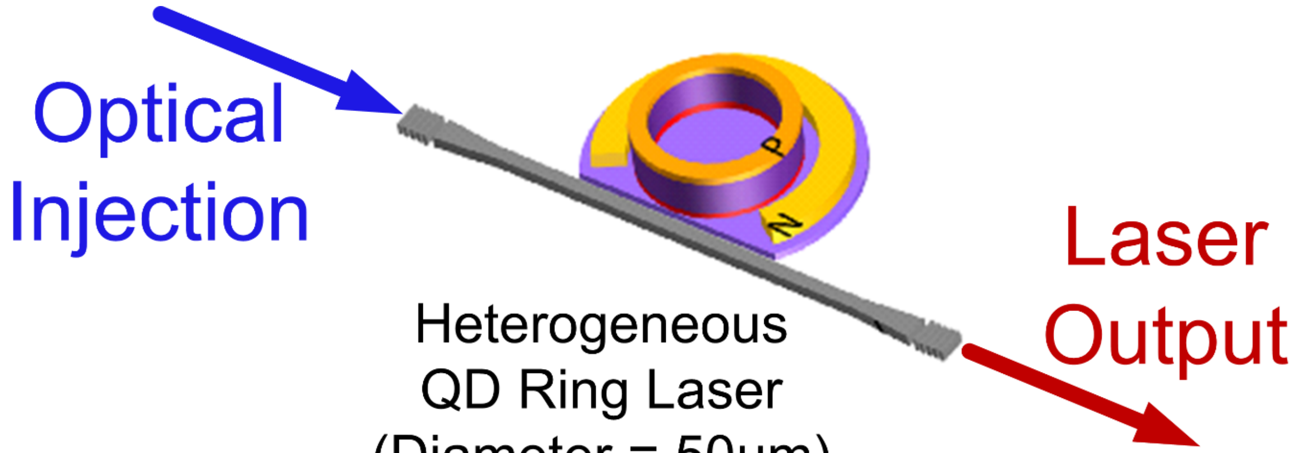
QD Microring Laser Design





- Hybrid Quantum Dot (QD) Microring Laser
  - D=50 μm, InAs QD active region (O-band)
- 5X lower threshold current (~1 to 3 mA) than quantum well counterparts
- Superior optical gain stability at the high temperature
- Fiber coupled output power: up to -10 dBm (10 dB grating coupler loss)
- Single-mode operation at O-band possible (with careful control)
  - Extinction ratio >60 dB, Side-mode suppression ratio > 45 dB

Optical Injection-Locked QD Ring Laser



Heterogeneous
QD Ring Laser
(Diameter = 50µm)

- O-band QD Laser typically has a low intrinsic bandwidth from 3 to 5 GHz
- Optical injection-locking technique:
    - Significantly enhance the modulation bandwidth from 3 to 19 GHz
    - Suppresses side modes for better single-mode operation
    - Bus-microring structure allows for OIL configuration without isolator
    - Small injection power (~90 µW) required to couple into the slave laser

Laser Injection Locking Theory

- $H(\Omega)$: Modulation response

$$H(\Omega) = A\frac{\Omega+p_0}{\Omega^3+q_2\Omega^2+q_1\Omega+q_0}$$

$$A = \frac{1}{e}a_N S$$

$$p_0 = k_c\sqrt{\frac{S_{inj}}{S}}(\cos\phi - \alpha\sin\phi)$$

$$q_2 = a_N S + \frac{1}{\tau_n} - \left(g - \frac{1}{\tau_p} - a_S S\right)$$

$$q_1 = a_N S(a_S S - g) - k_c^2\frac{S_{inj}}{S} - \left(g - \frac{1}{\tau_p} - a_S S\right)\left(a_N S + \frac{1}{\tau_n} + k_c\sqrt{\frac{S_{inj}}{S}}\cos\phi\right)$$

$$q_0 = -k_c a_N\sqrt{S_{inj}S}(a_S S - g)(-\alpha\sin\phi + \cos\phi) - \left[\left(g - \frac{1}{\tau_p} - a_S S\right)k_c\sqrt{\frac{S_{inj}}{S}}\cos\phi + k_c^2\frac{S_{inj}}{S}\right](a_N S + \frac{1}{\tau_n})$$

- S_{inj}: injection photon number
- $S_{inj} = 0$, then H is a simple 2-pole response as $p_0 = 0$ and $q_0 = 0$

C.-H. Chang, *et al.*, “Injection Locking of VCSELs”, *Journal of selected topics in quantum electronics*, 2003

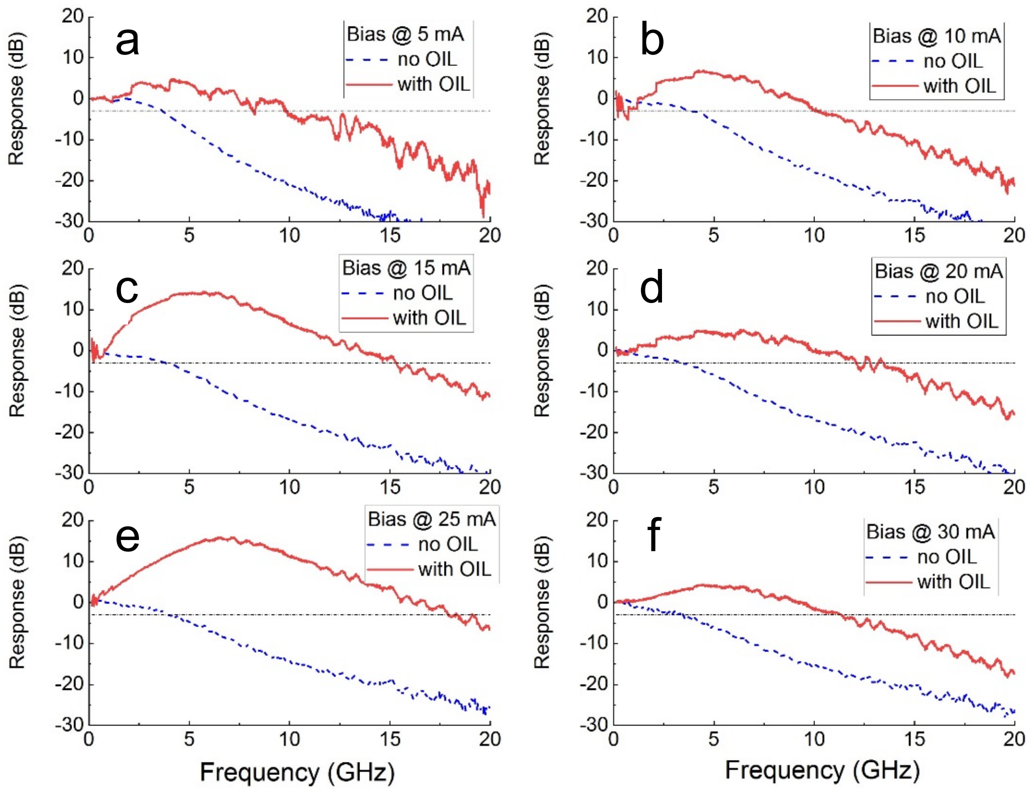
Laser Injection Locking Theory

- $H(\Omega)$: Modulation response
- $S_{inj} > 0$, 3-order denominator determines characteristics
  - 3 real poles: over-damped response
  - 1 real pole and 2 complex conjugated poles (BW extension case)
    - 2 conjugated poles determines resonate frequency and damping
    - The curve can be fitted as below with meaningful parameters, parasitic pole frequency f_0, resonance frequency f_r, and damping factor γ

$$|\boldsymbol{H}'(\boldsymbol{f})|^2 = \left(\frac{\mathbf{1}}{\mathbf{1} + \left(\frac{\boldsymbol{f}}{\boldsymbol{f}_0}\right)^2}\right)\left(\frac{\mathbf{1}}{\left(\mathbf{1} - \left(\frac{\boldsymbol{f}}{\boldsymbol{f}_r}\right)^2\right)^2 + \left(\frac{\boldsymbol{\gamma}}{\mathbf{2}\boldsymbol{\pi}\boldsymbol{f}_r}\right)^2\left(\frac{\boldsymbol{f}}{\boldsymbol{f}_r}\right)^2}\right)$$

C.-H. Chang, *et al.*, “Injection Locking of VCSELs”, *Journal of selected topics in quantum electronics*, 2003
B. J. Thibeault, *et al.*, “High-speed characteristics of low-optical loss oxide-apertured vertical-cavity lasers”, *IEEE Photon Technol*, 1997

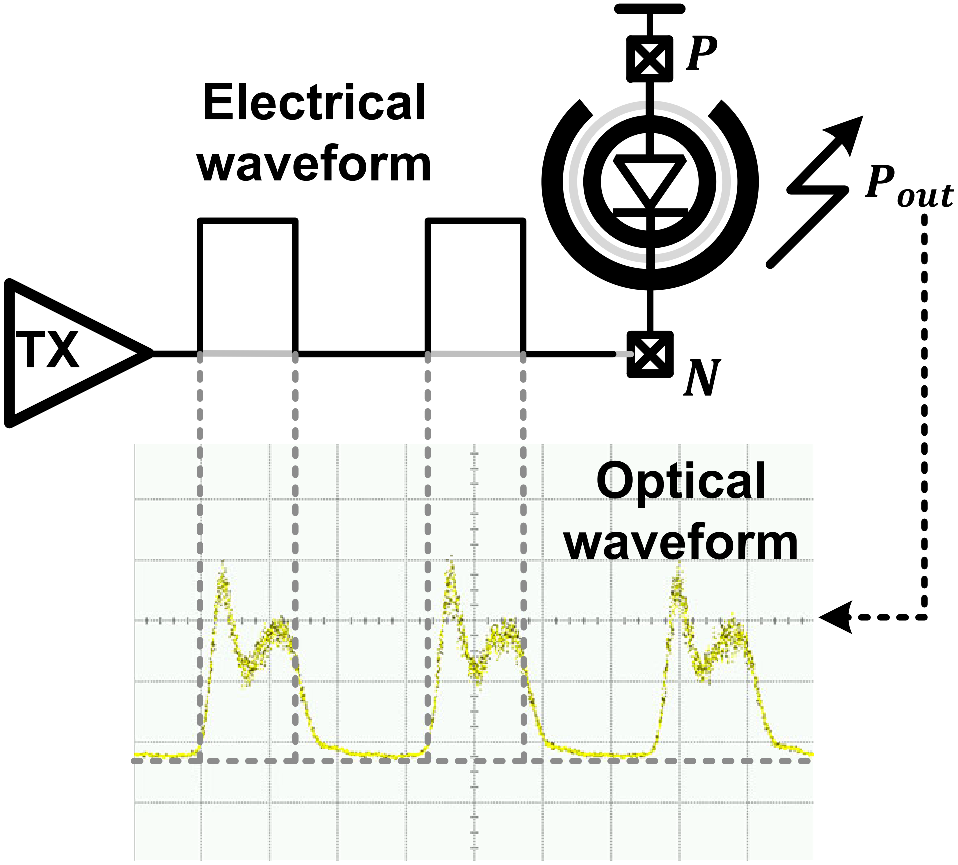
Direct Modulation Response



a~f: laser current bias from 5 to 30 mA

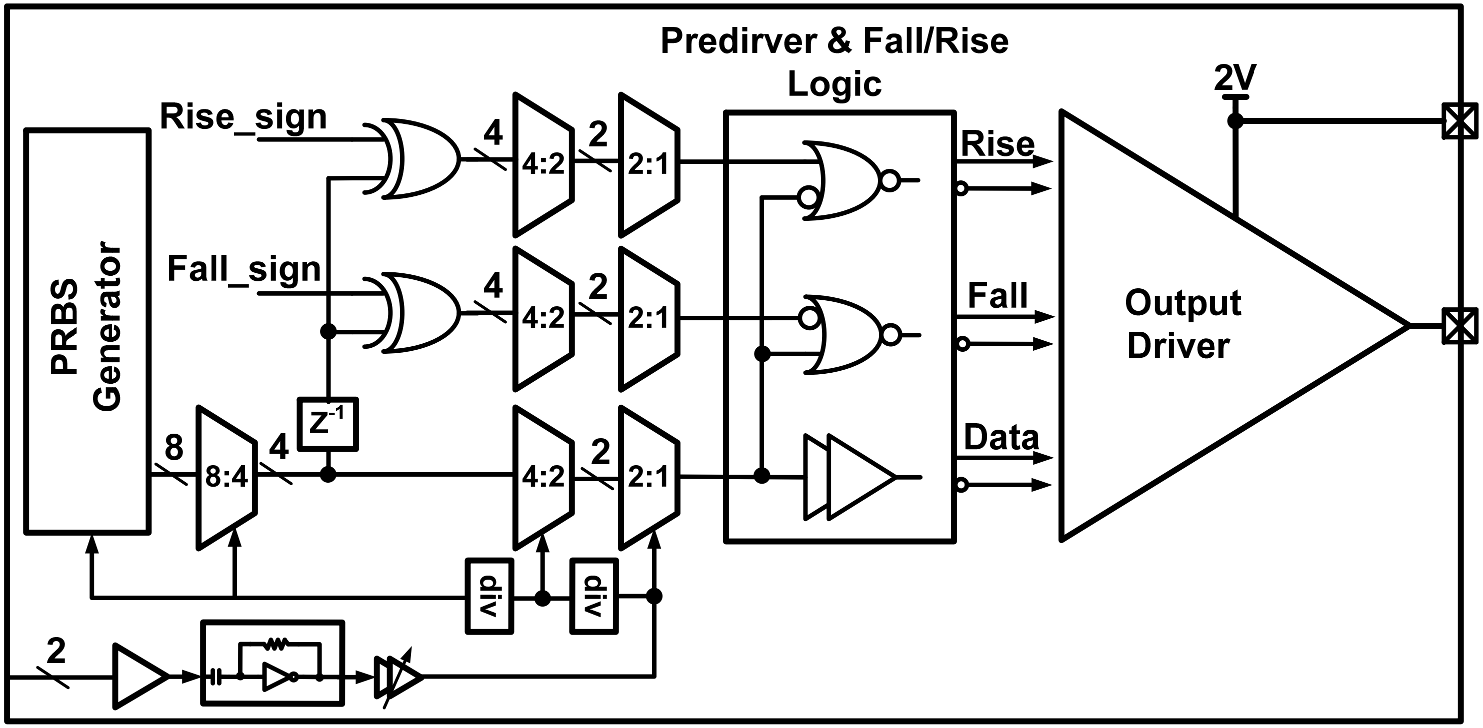
- Bandwidth is extended by the peaking located at around 5 to 7 GHz
- Without OIL, modulation bandwidth was between 2.6 and 4 GHz when bias current increased from 5 to 25 mA
- With OIL, modulation bandwidth is extended nearly 5 times
- Peaking is reduced at bias current 30 mA due to self-heat effect

Microring Laser Non-linear Optical Dynamic



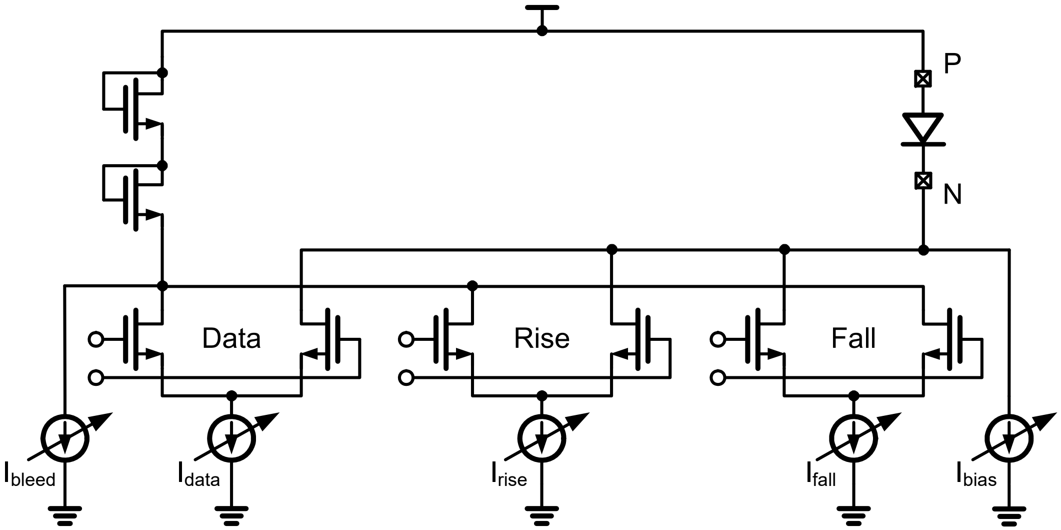
- Directly modulated QD microring laser
- Optical response is current dependent
- Observe a fast and underdamped rising edge and a slow and a overdamped falling edge
- Applying asymmetric FFE can achieve a better eye-diagram

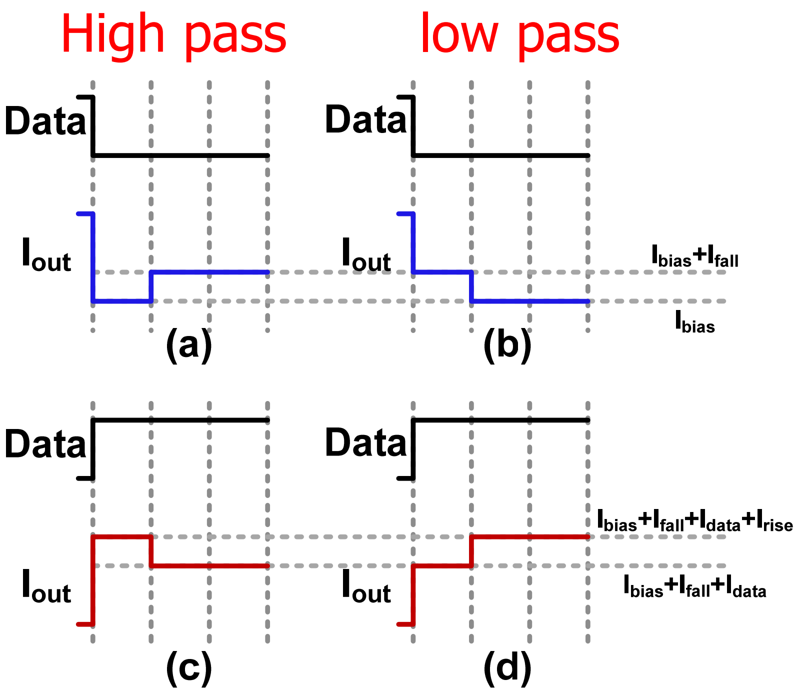
QD Microring Laser Driver



- Half rate architecture
- Pre-driver generate fall/rise pulses with independent sign
- Current mode output driver w/ diode replica reduces the supply noise

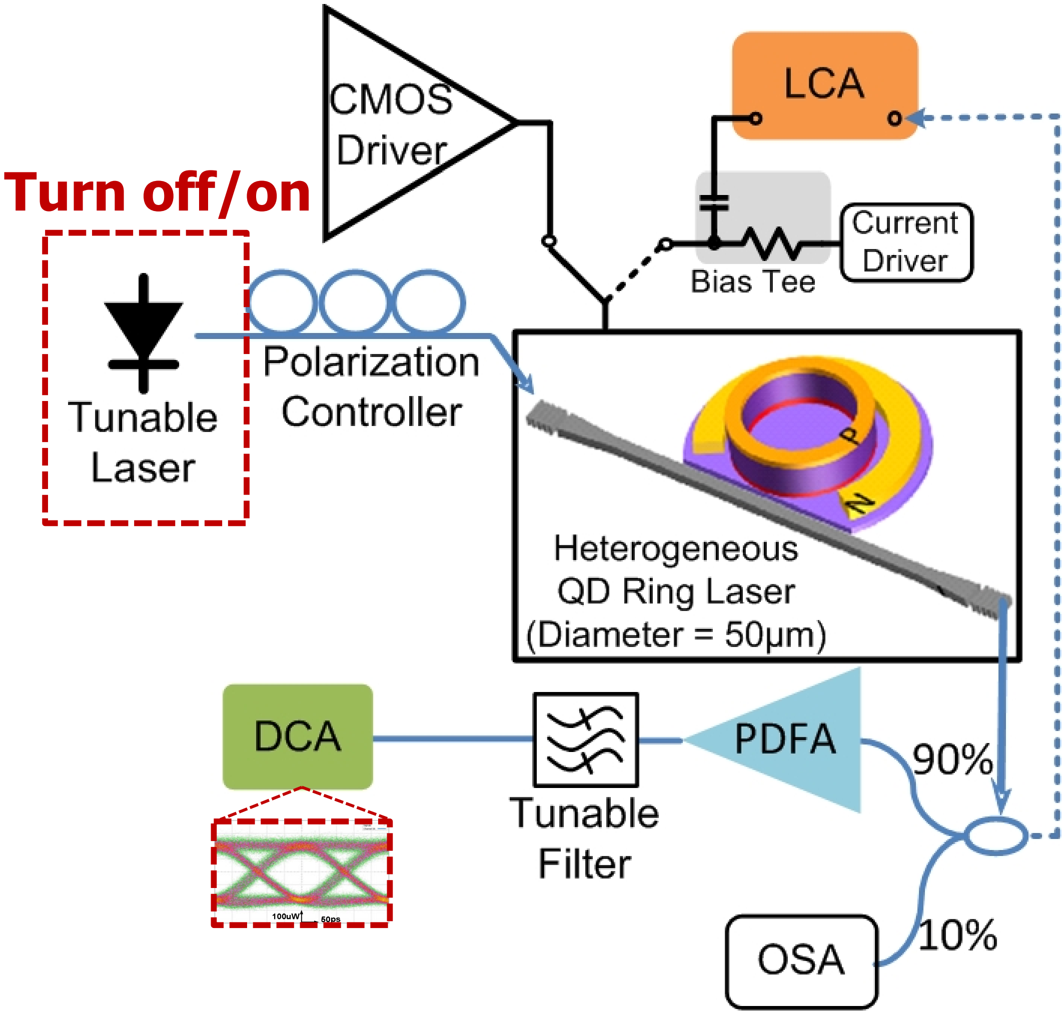
CML Output Driver with Asymmetric FFE





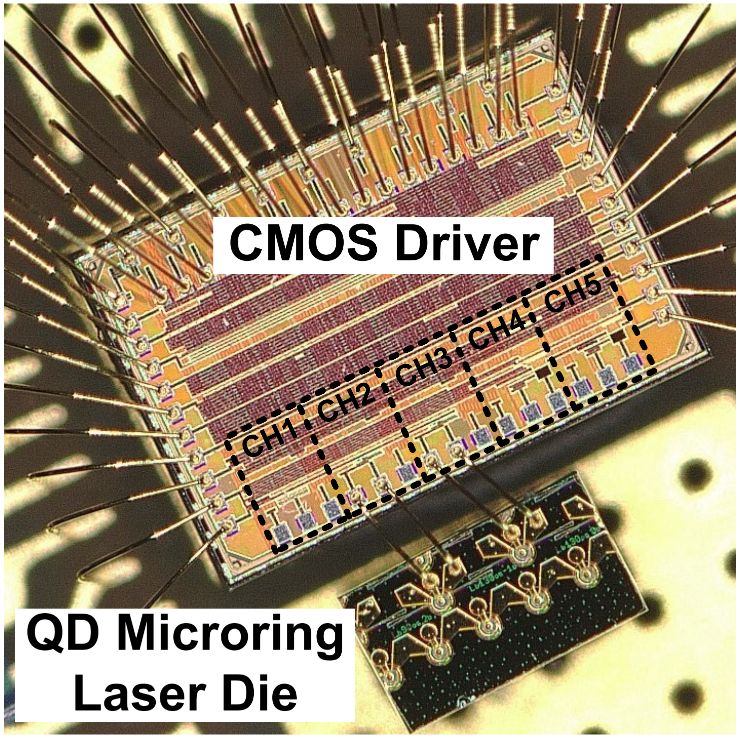
- I_{bias}: Control laser bandwidth
- I_{data}: Control current swing
- I_{fall}: Reduce/increase current on data fall depending on tap sign (FFE)
- I_{rise}: Reduce/increase current on data rise depending on tap sign (FFE)
- I_{bleed}: Provides biasing for the replica
- Independently perform the high/low pass filter behaviors on rising and falling edges

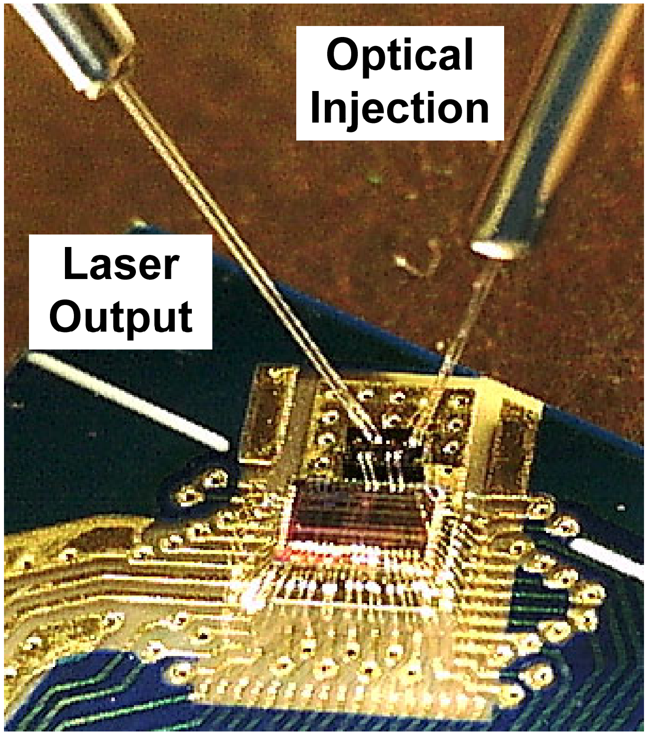
Measurement Setup



- A commercial tunable laser was used as master laser
- Grating coupler at the ends of bus waveguide to couple light into/out of a fiber
- 10% of the power from DUT is monitored on an optical spectrum analyzer
- Remaining 90% of the power goes through a fiber amplifier and a tunable optical filter
- The eye diagram is observed on a digital communication analyzer (DCA)

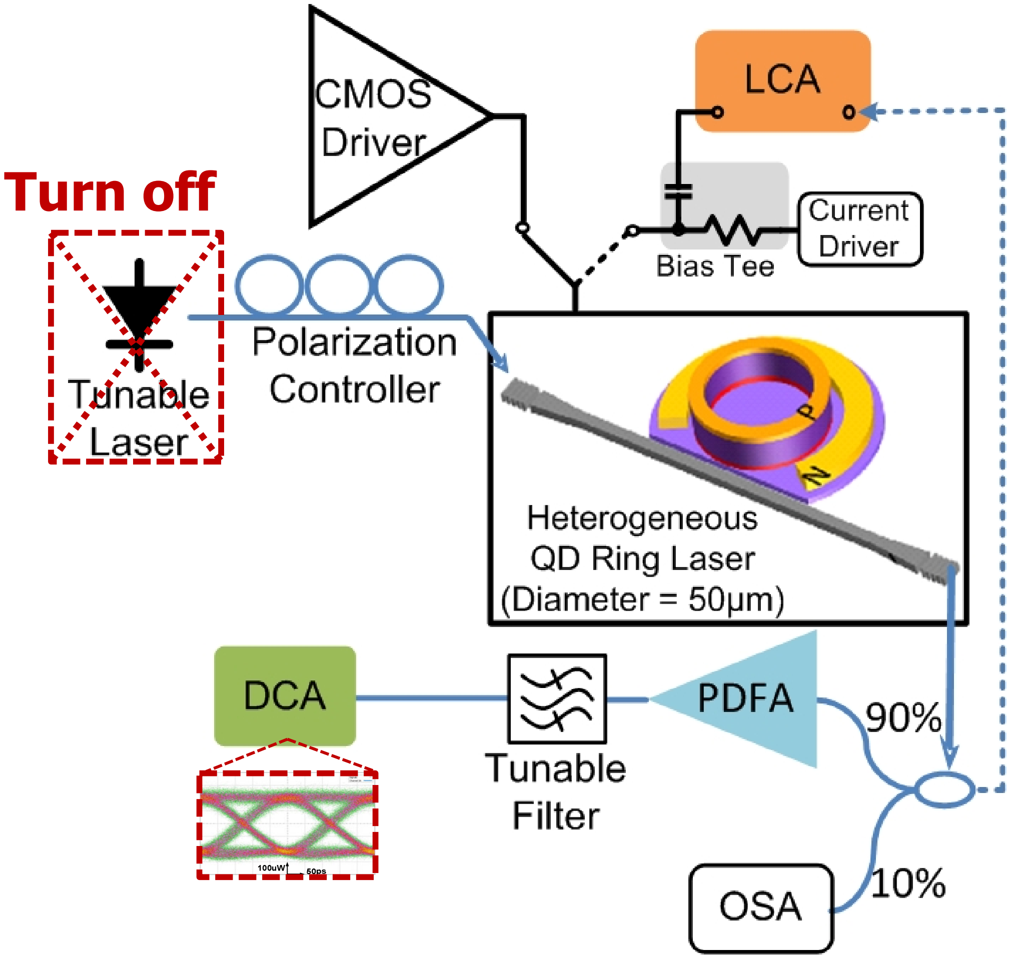
Prototype and Optical Measurement Setup



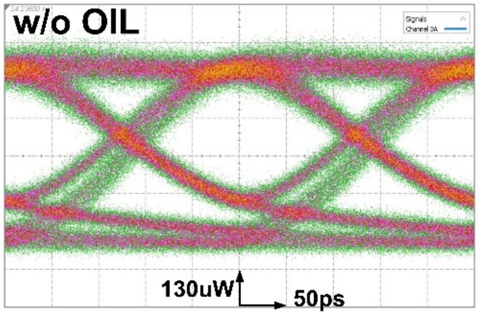


- Prototype is fabricated in a 28 nm CMOS process
- Hybrid chip-on-board integration approach
- Cleaved single-mode fiber (SMF) for input and output coupling

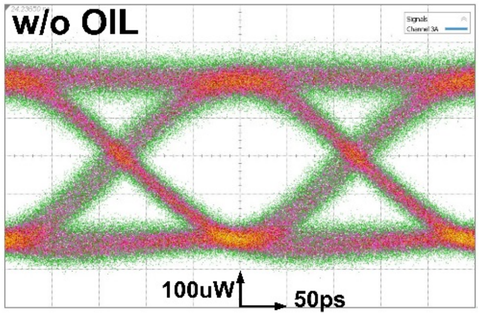
Measurement Results (4 Gb/s)



4 Gb/s w/o FFE

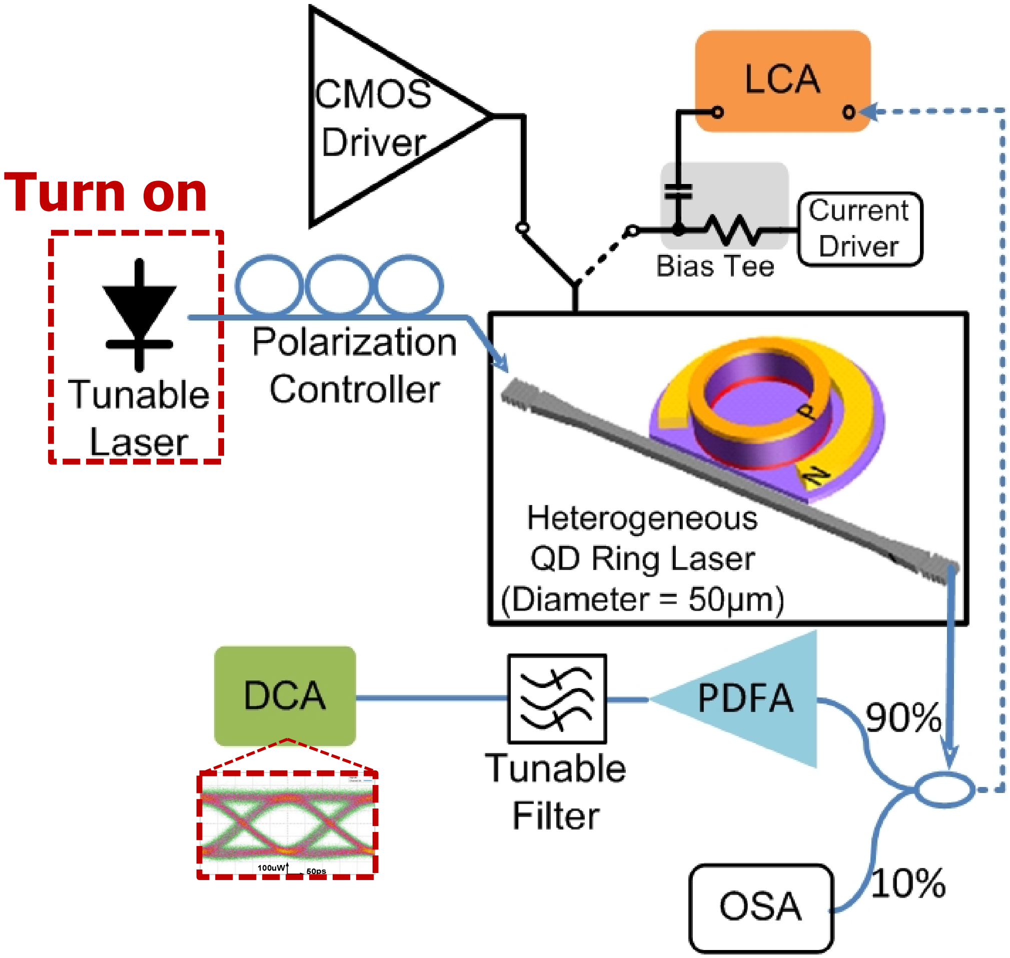


4 Gb/s w/ FFE



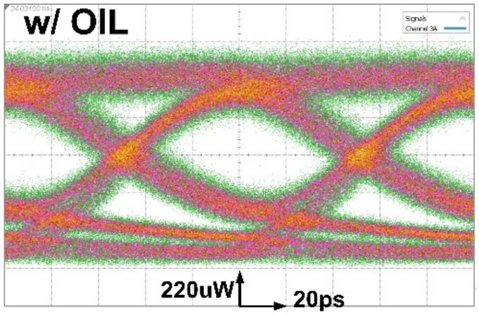
- Laser bias current ~20 mA
- OIL is disable by turning off tunable laser
- Applying asymmetric 2-tap FFE can improve eye opening

Measurement Results (10 and 22 Gb/s)

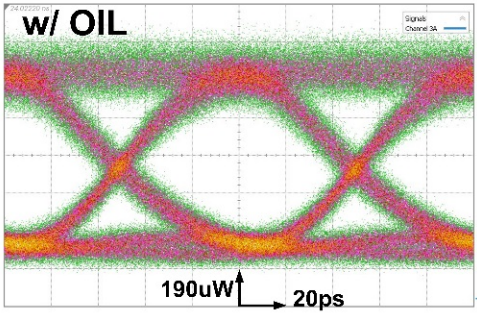


Laser bias current ~20 mA

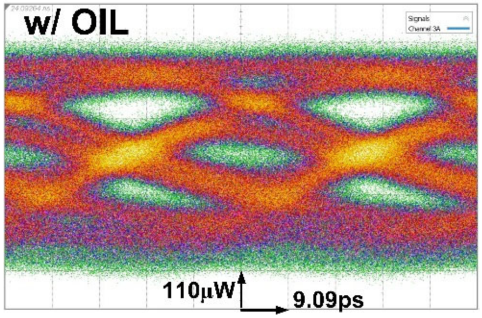
10 Gb/s w/o FFE



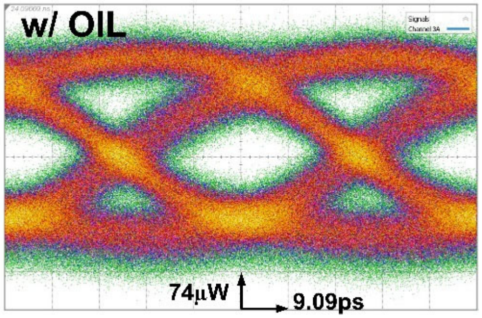
10 Gb/s w/ FFE



22 Gb/s w/o FFE



22 Gb/s w/ FFE



- OIL is enabled by aligning tunable laser wavelength to one of the lasing wavelengths in slave microring laser
- Applying OIL can boost data-rate to 10 Gb/s or higher
- Applying asymmetric 2-tap FFE can improve eye opening
- Using OIL and asymmetric 2-tap FFE can achieve the best performance 22 Gb/s

Comparison

References	Roshan-Zamir OFC 2018	Fan OFC 2019	This Work
DML Device	Quantum Well Microring Laser	Quantum Dot Microring Laser	Quantum Dot Microring Laser
CMOS Technology	65nm	65nm	28nm
Data Rate Per Channel (Gb/s)	14	12	22
Number of Channels	5	5	4
Energy Efficiency (pJ/bit)	10.3	10.8	3.2
Integrated Driver	Yes	Yes	Yes
Optical Injection Locking	No	No	Yes

Optical Injection-Locked Quantum-Dot Microring Laser Transmitter Summary

- QD microring laser has WDM potential to dramatically increase the pin efficiency
- OIL can significantly enhance the modulation bandwidth 4~5 times
- OIL and asymmetric 2-tap FFE techniques enable 22Gb/s operation which is the highest NRZ direct modulation speed of an O-band QD Laser on silicon
- The first hybrid integrated and directly modulated OIL QD microring laser system