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

## Lecture 8: VCSEL TXs

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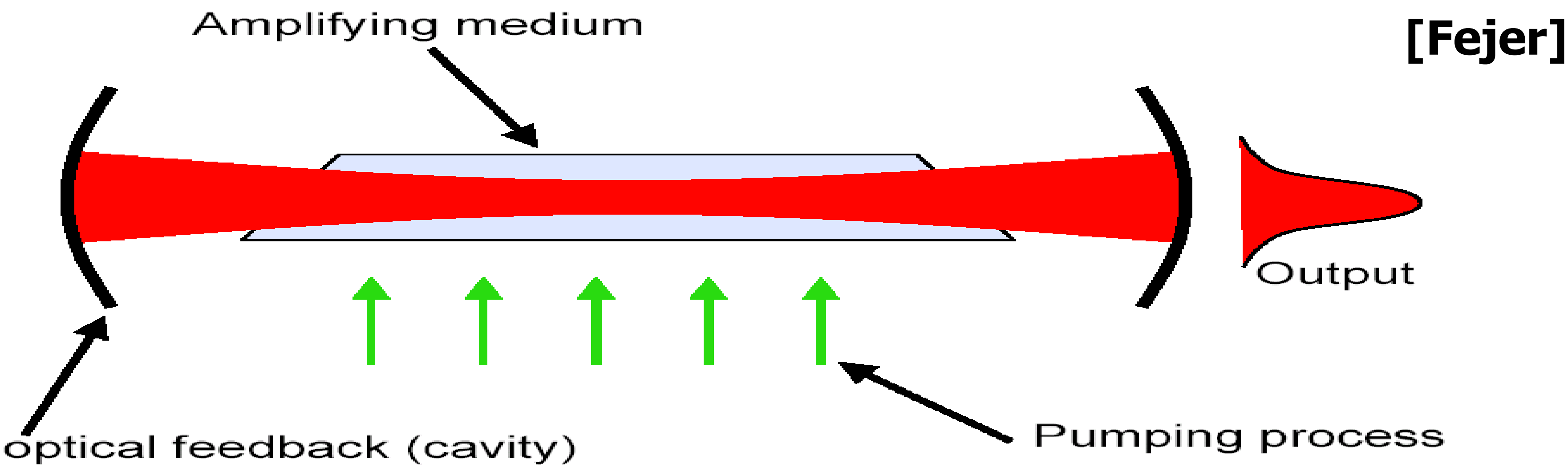
# Announcements

- Homework 3 is due Mar 31
- Reading
  - Sackinger Chapter 8

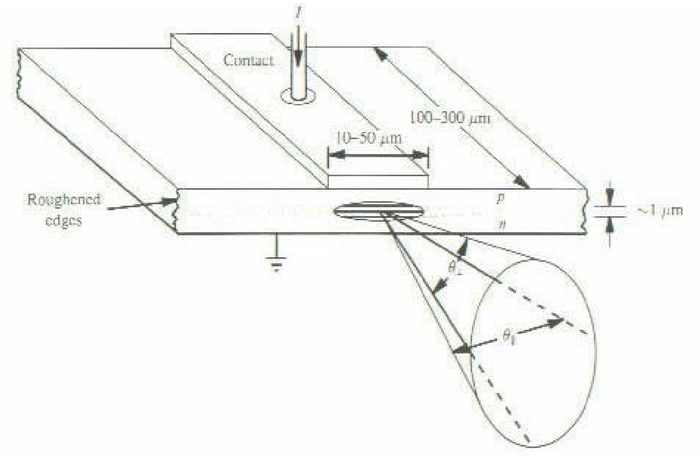
# What is a Laser?

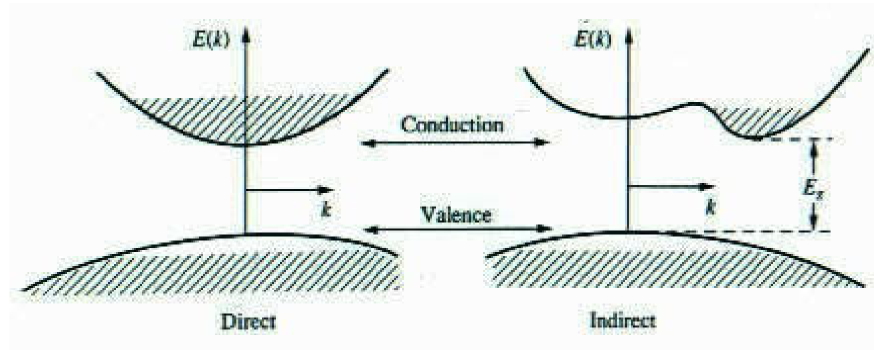



- **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation
- **L**ight **O**scillation by **S**timulated **E**mission of **R**adiation
- Lasers are optical oscillators that emit coherent light through the process of stimulated emission
- 3 Elements in all lasers
  - Amplifying Medium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

# Semiconductor Diode Lasers

**[Verdeyen]**



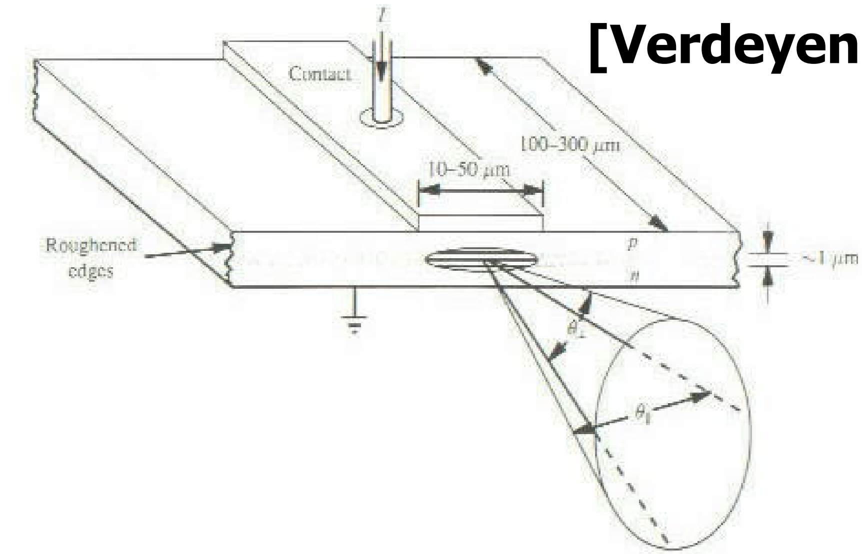




- Can be made with simple p-n junction
- Based on transitions between bands
  - Direct bandgap materials necessary
  - Si isn't ⇒ GaAs, InP
- Pumped electrically with current source
- Efficient device requires confinement of both carriers and photons
  - Leads to the use of heterostructures

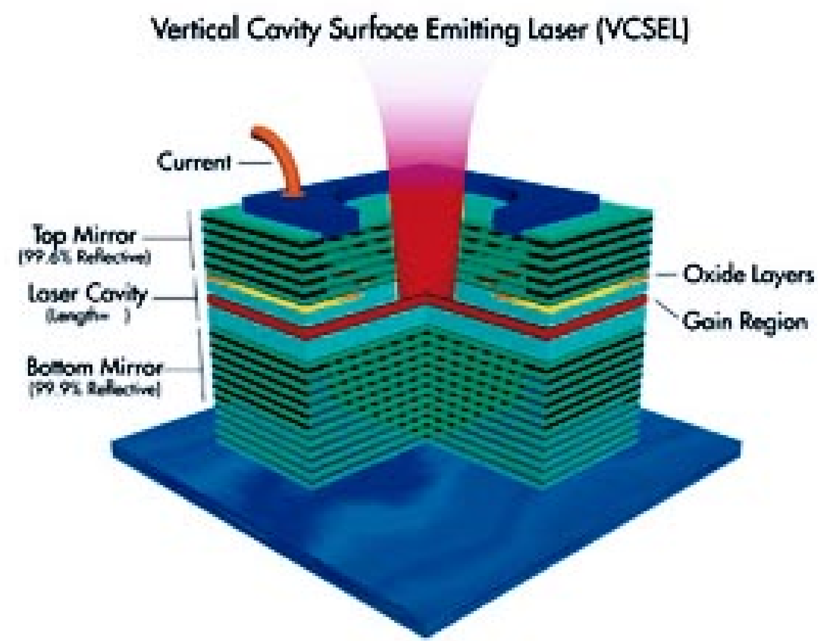
# Edge Emitters & VCSELs

**[Verdeyen]**

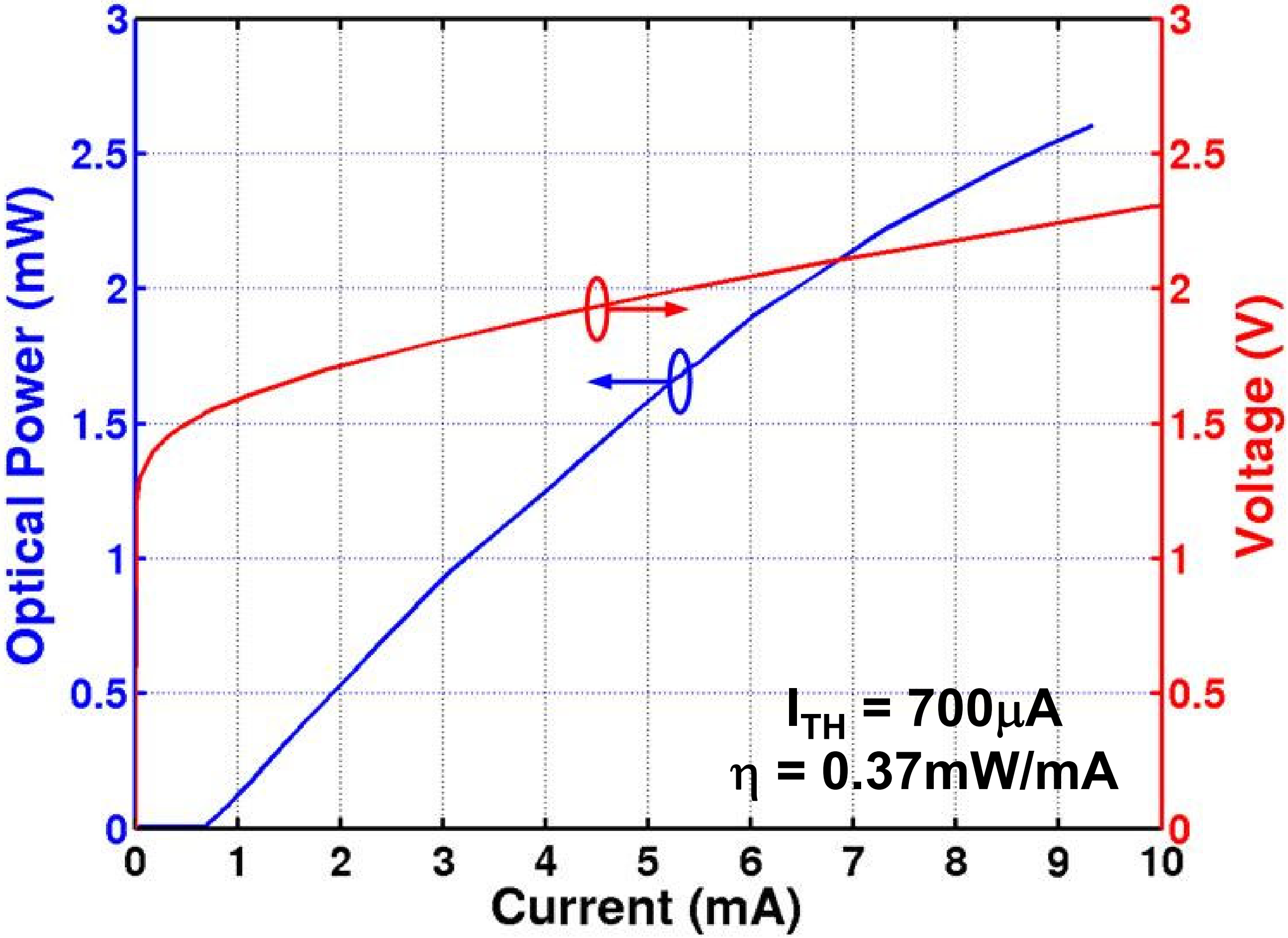
- Edge Emitters
  - Advantage
    - Historically easier to manufacture
  - Disadvantages
    - Emit light in an elliptical mode
    - Higher testing and packaging costs




- VCSELs – Vertical Cavity Surface Emitting Lasers
  - Advantages
    - Can make 2-D arrays
    - Emit light in a circular output mode
    - Smaller device ⇒ Lower operating currents
    - Lower testing and packaging costs
  - Disadvantage
    - Hard to manufacture due to growth of high reflective mirrors

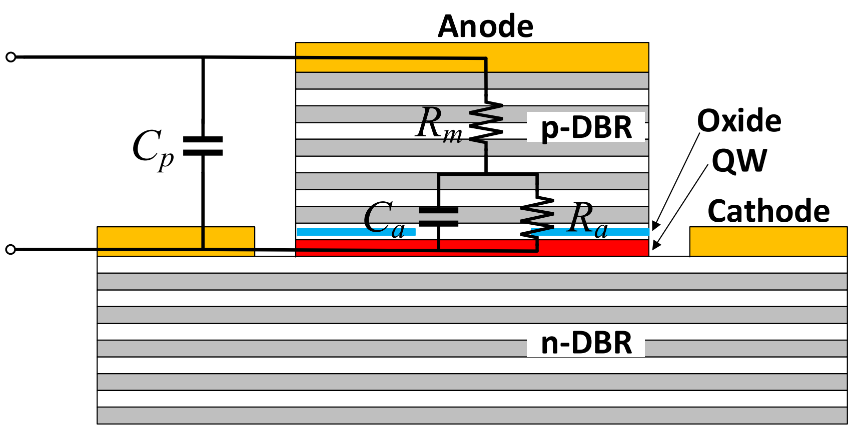


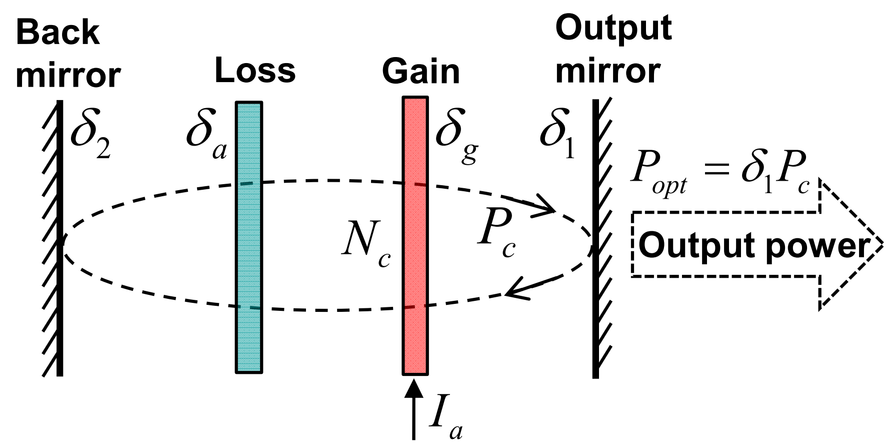
# VCSEL Light-Current-Voltage (LIV) Curve



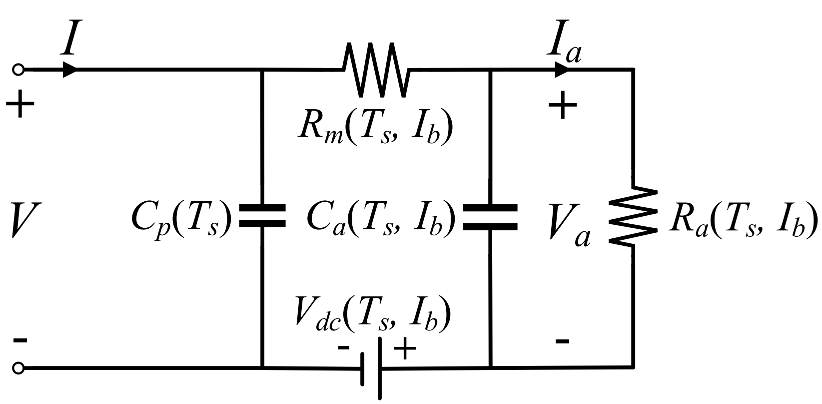

$$P_o = \eta(I - I_{TH}) \qquad \text{Slope Efficiency } \eta = \frac{\Delta P}{\Delta I} \left(\frac{\text{W}}{\text{A}}\right)$$

# VCSEL Model




### Electrical Input Stage




### Optical Output Stage

$I_a$ →

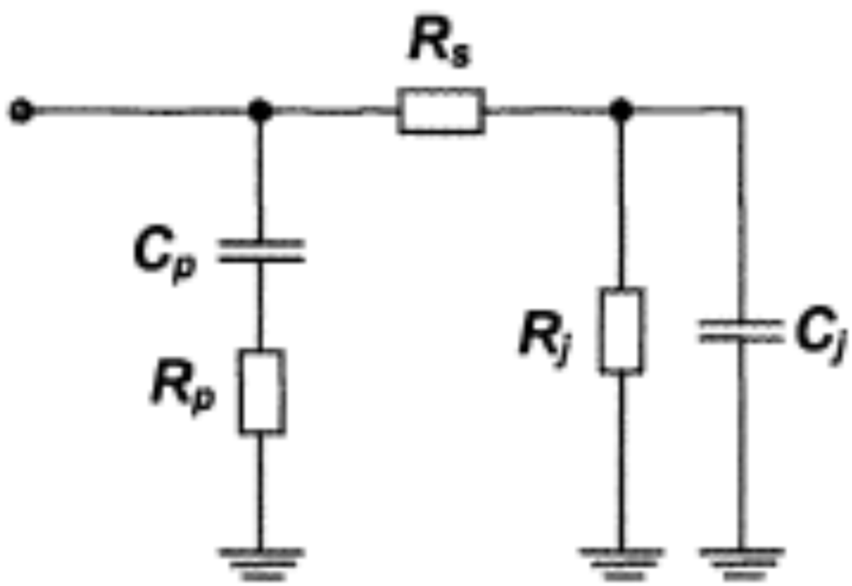
$$\frac{dN_c}{dt} = \frac{\eta_i(T)\cdot\left[I_a - I_{th}(T)\right]}{q} - \delta_g(T)\cdot\frac{P_c}{h\nu}$$

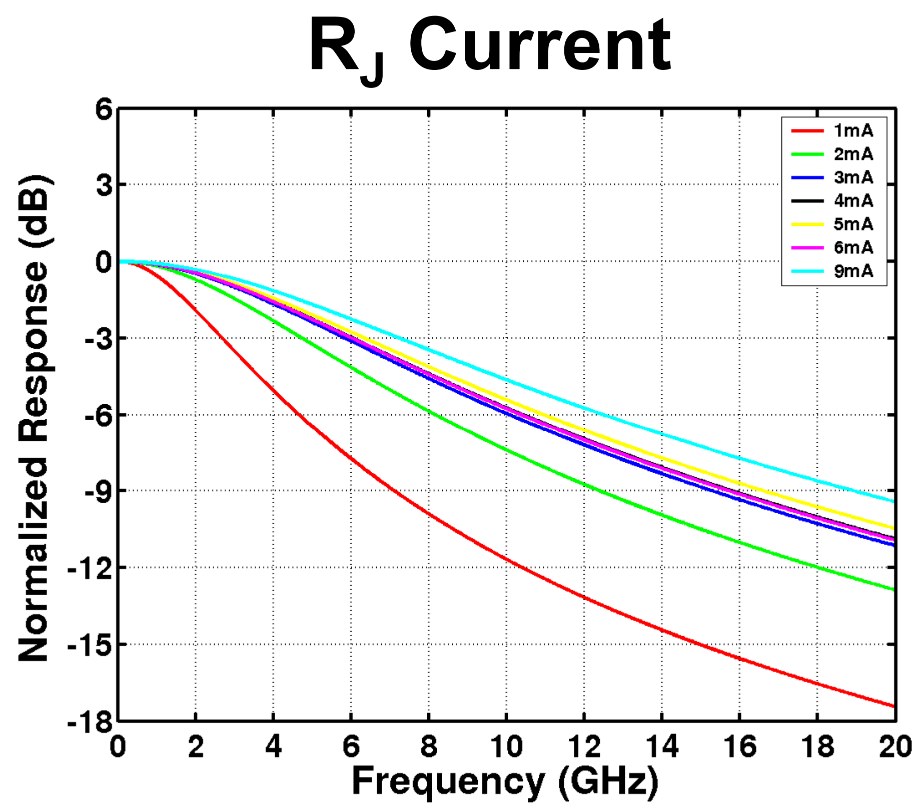
$$\frac{dP_c}{dt} = \left[\delta_g(T) - \delta_c\right]\cdot\frac{P_c}{\tau_c} + P_{sp}(T)$$

→ $P_{opt} = \delta_1 P_c$

- Capture thermally-dependent electrical and optical dynamics
- Provide dc, small signal, and large-signal simulation capabilities

# 10Gbps VCSEL Electrical Model




- Models finite Q pad capacitance, mirror series resistance, and junction RC
- Frequency response dominated by current dependent $R_J C_J$
  - $f_{3dB}$ about 6.5GHz with I≥3mA

# Laser Rate Equations

- Two coupled differential equations describe the electron density (N) and the photon density ($N_p$) interaction

$$\text{Electron Density Rate Equation}: \frac{dN}{dt} = \frac{I}{qV} - \frac{N}{\tau_{sp}} - GNN_p$$

Stimulated emission recombination

Rate of electron density change

Injected electrons generation

Non-radiative & spontaneous emission recombination

$I$ = injected current

$V$ = cavity volume

$G$ = stimulated emission coefficient

$\beta_{sp}$ = spontaneous emission coefficient

$\tau_p$ = photon lifetime

$$\text{Photon Density Rate Equation}: \frac{dN_p}{dt} = GNN_p + \beta_{sp}\frac{N}{\tau_{sp}} - \frac{N_p}{\tau_p}$$

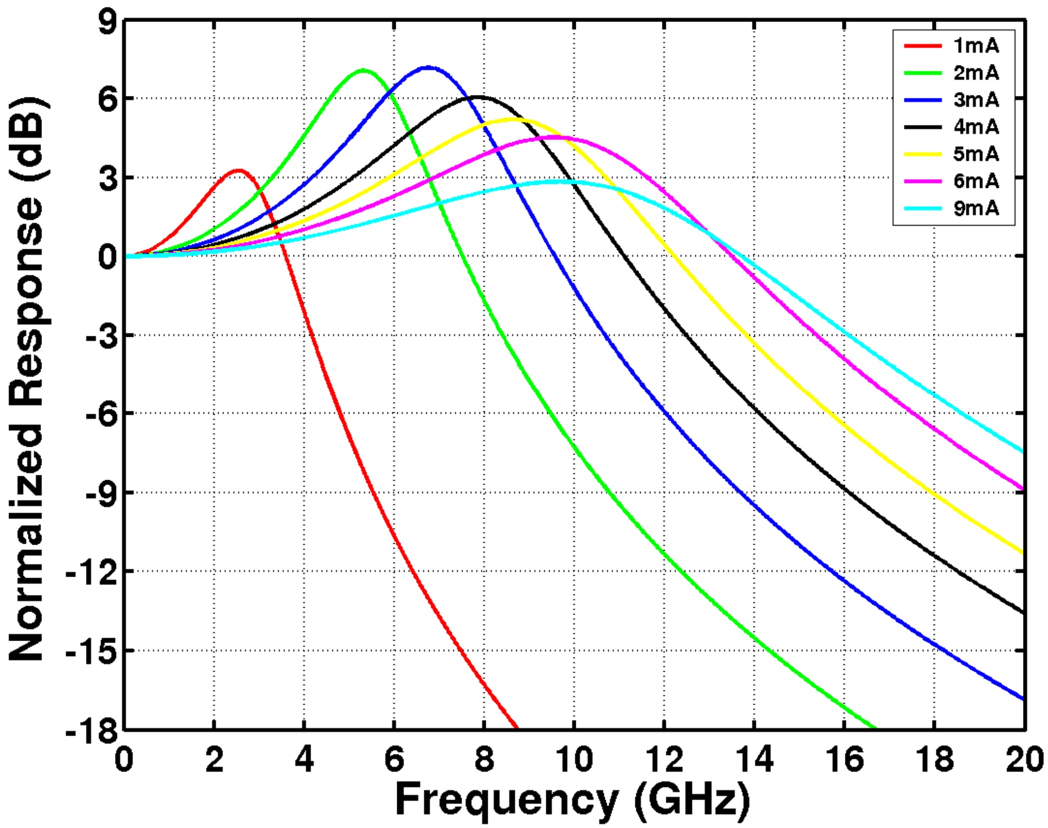
Photons loss due to optical absorption and scattering

Rate of photon density change

Stimulated emission

Spontaneous emission

# VCSEL Rate Equation Frequency Response




$$\omega_R = \sqrt{\frac{GN_{pdc}}{\tau_p}} \quad \text{(Proportional to } \sqrt{I_{avg}}\text{)}$$

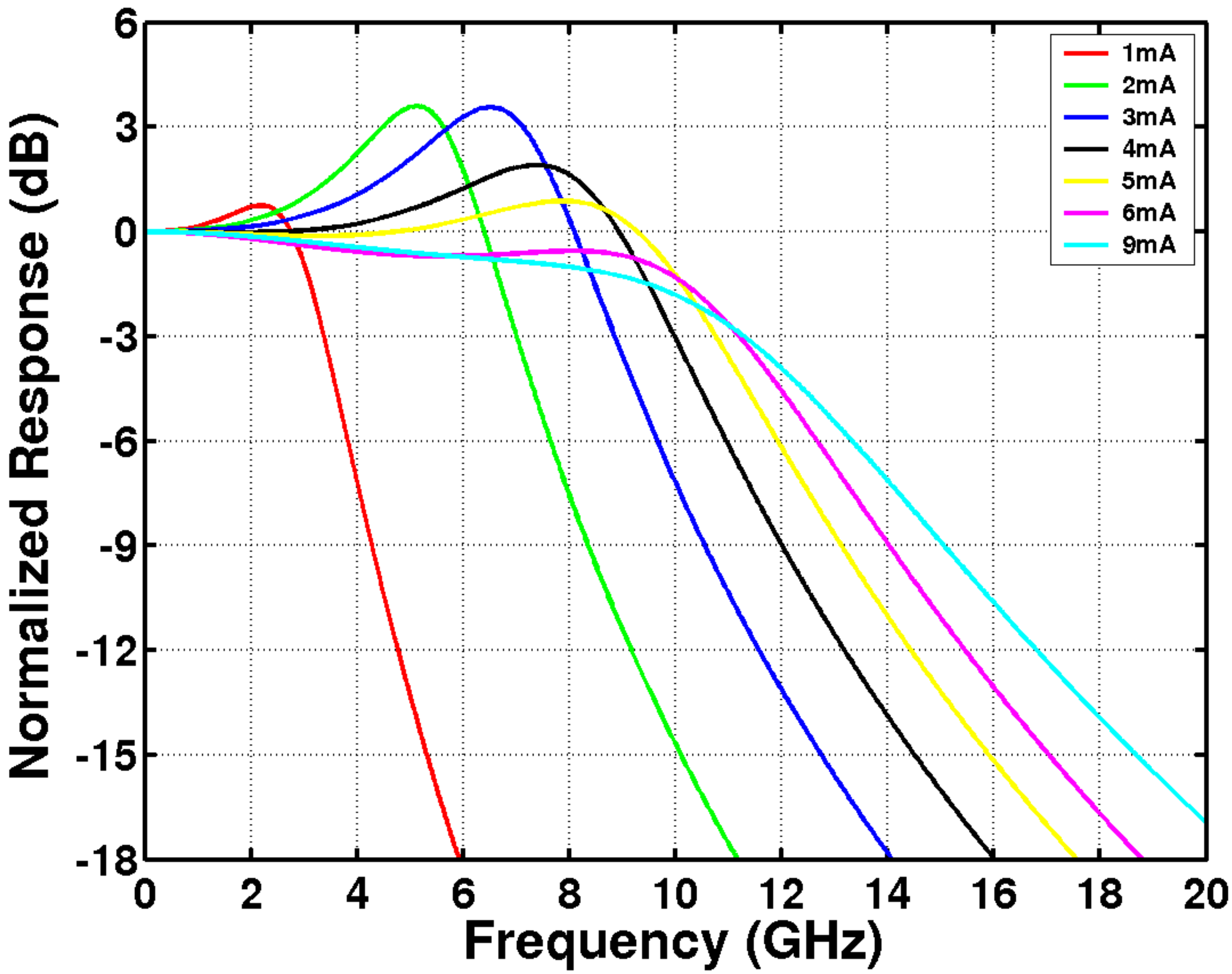
$$\zeta = \frac{GN_{pdc} + \frac{1}{\tau_{sp}}}{2\sqrt{\frac{GN_{pdc}}{\tau_p}}}$$

$$\frac{P_{ac}(\omega)}{I_1(\omega)} = \frac{h\nu v_g \alpha_m}{q} \frac{GN_{pdc}}{-\omega^2 + j\omega\left(GN_{pdc} + \frac{1}{\tau_{sp}}\right) + \frac{GN_{pdc}}{\tau_p}}$$

$\upsilon_g$ = group velocity

$\alpha_m$ = mirror loss coefficient

# 10Gb/s VCSEL Frequency Response



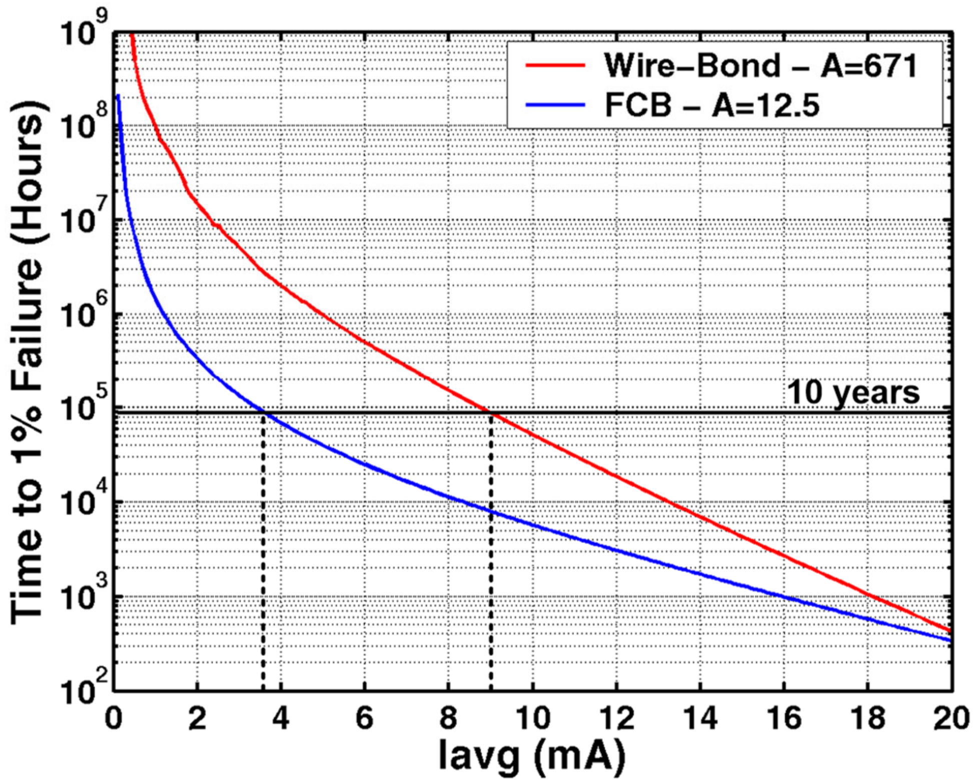

$$BW \propto \sqrt{I_{avg} - I_{TH}}$$

D. Bossert *et al*, "Production of high-speed oxide confined VCSEL arrays for datacom applications," *Proceedings of SPIE*, 2002.

# VCSEL Reliability

- Mean Time to Failure (MTTF) is inversely proportional to current density squared
- Failure time modeled with lognormal distribution
- Higher mechanical stress reduces flip-chip bond reliability
- Trade-off between reliability and bandwidth
  - $MTTF \propto \frac{1}{BW^4}$

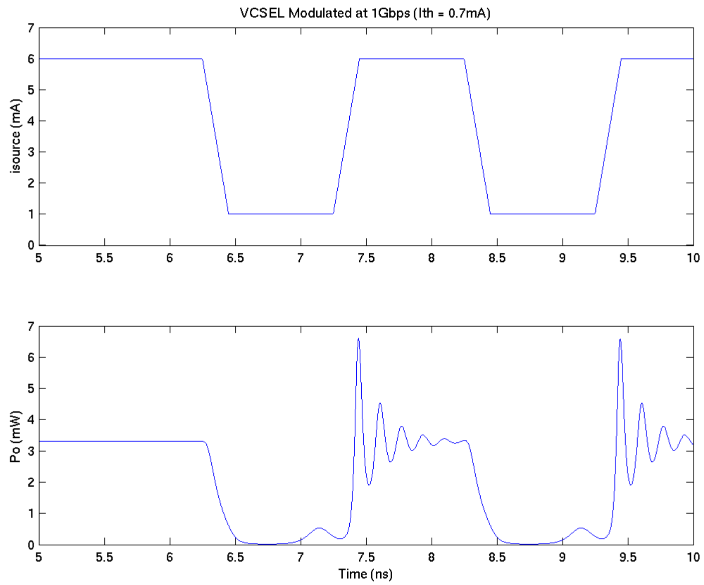
$$MTTF = \frac{A}{j^2} e^{\left(\frac{E_A}{k}\right)\left(\frac{1}{T_j} - \frac{1}{373}\right)}$$



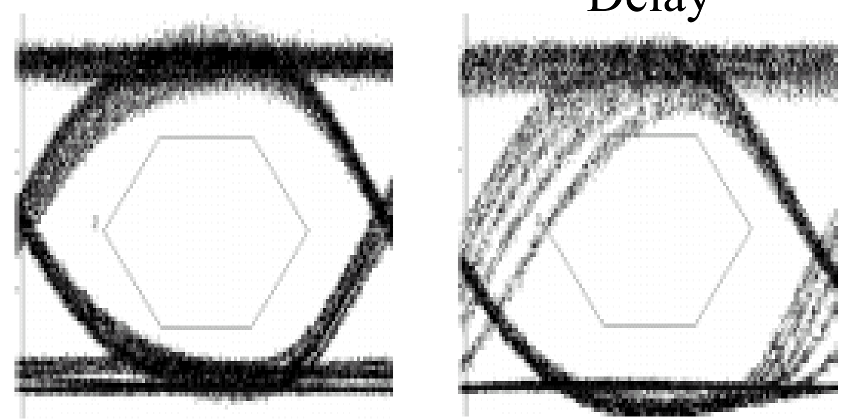


M. Teitelbaum and K. Goossen, "Reliability of Direct Mesa Flip-Chip Bonded VCSEL's," *LEOS*, 2004.
C. Helms *et al*, "Reliability of Oxide VCSELs at Emcore," *Proceedings of SPIE*, 2004.

# Laser Rate Equations – Transient Response




Turn-on Delay



[Honeywell]

- Laser step response displays relaxation oscillations due to low damping
- Turn-on delay ($t_d$) occurs if the laser is biased below threshold
  - Causes data-dependent jitter

$$t_d = \tau_{sp} \ln\left[\frac{I_1 - I_0}{I_1 - I_{TH}}\right]$$

# Chirp

- VCSELs also have additional unwanted frequency modulation called chirp
- The linewidth in this case can be approximated as

$$\Delta\lambda \approx \frac{\lambda^2}{c} B\sqrt{\alpha^2 + 1}$$

where $\alpha$ is the *chirp parameter* or *linewidth enhancement factor*.

- The $\alpha$ parameter relates the change in optical frequency to the change in optical power

$$\Delta f(t) \approx \frac{\alpha}{4\pi} \cdot \frac{d}{dt} \ln P_{out}(t)$$

- Directly modulated lasers have positive $\alpha$ values, implying that for a rising edge the laser will blue-shift (higher frequency/shorter $\lambda$) and red-shift for a falling edge

# Relative Intensity Noise (RIN)

- VCSELs have occasional spontaneous emissions which add amplitude and phase noise to it's coherent light output
- The resulting intensity fluctuations are known as relative intensity noise (RIN)
- At the receiver, this will get converted to an equivalent electrical noise component by the photodetector which is approximately proportional to the received signal power

$$\overline{i_{n,RIN}^2} = RIN \cdot I_{PIN}^2 \cdot BW_n$$

Here *RIN* is a parameter characterizing the laser RIN noise measured in dB/Hz. The resulting SNR is

$$SNR = \frac{I_{PIN}^2}{\overline{i_{n,RIN}^2}} = \frac{1}{RIN \cdot BW_n}$$

Can't improve SNR by increasing the laser power!

# RIN Power Penalty

Assuming a laser with $RIN = -135dB/Hz$ and a 10GHz receiver noise bandwidth, the SNR is

$$SNR = \frac{I_{PIN}^2}{\overline{i_{n,RIN}^2}} = \frac{1}{10^{\frac{-135dB/Hz}{10}}(10GHz)} = 3.16\times10^3 = 35dB$$

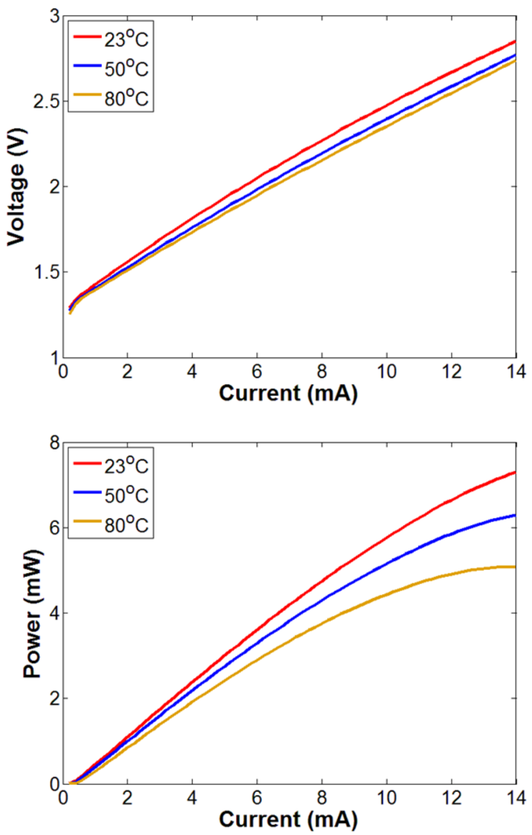
- This SNR is fine for digital NRZ signaling, but may be an issue for analog optical links for applications such as cable TV
- RIN noise does introduce an additional power penalty

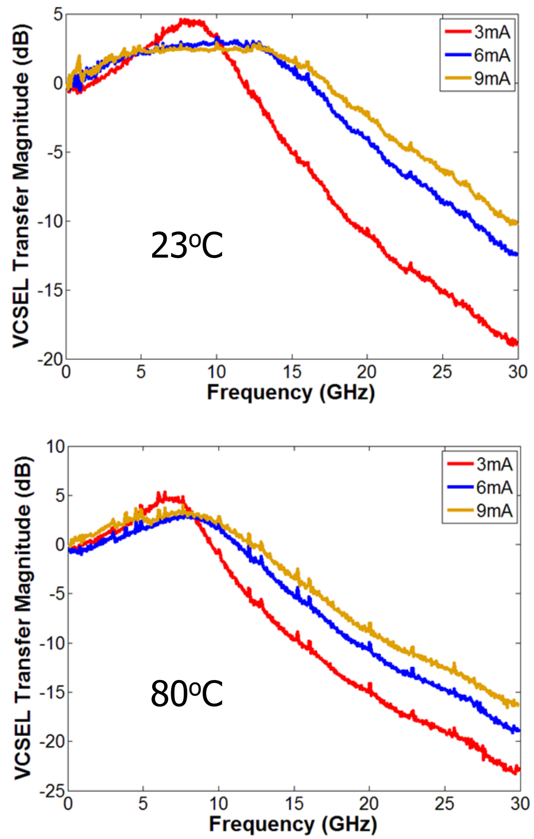
$$PP = \frac{1}{1-Q^2\cdot RIN\cdot BW_n}$$

For the above example, the BER $=10^{-12}$ power penalty is

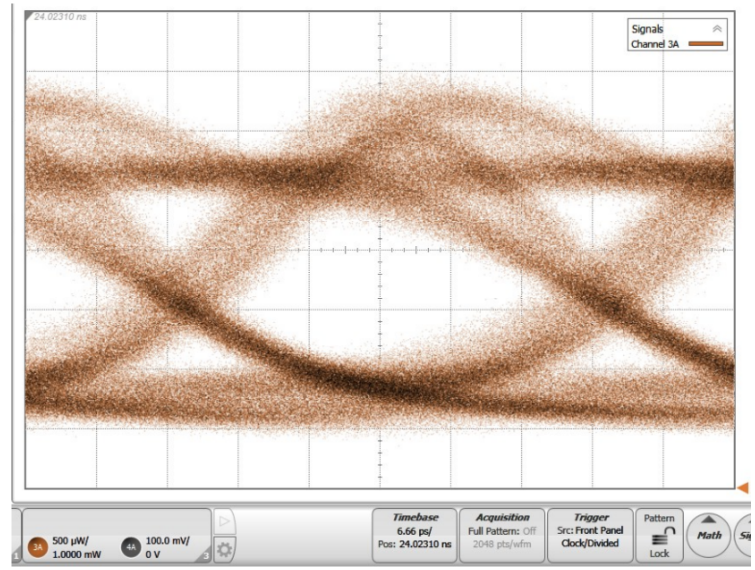
$$PP = \frac{1}{1-(7.035)^2\left(\frac{1}{3.16\times10^3}\right)} = 1.016 = 0.069dB$$

# Temperature-Dependent Performance




25Gb/s

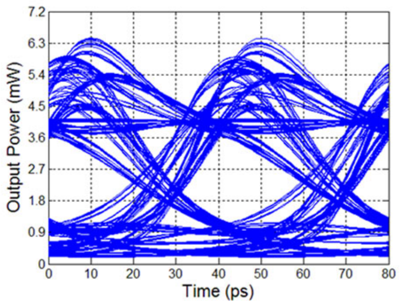


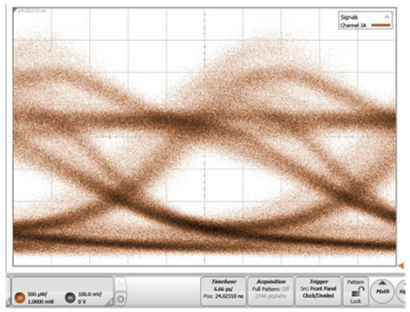

- Optical power-current-voltage (L-I-V) response is temperature-dependent
- Bandwidth is bias and temperature dependent

# Measured and Simulated 25Gb/s Eye Diagrams

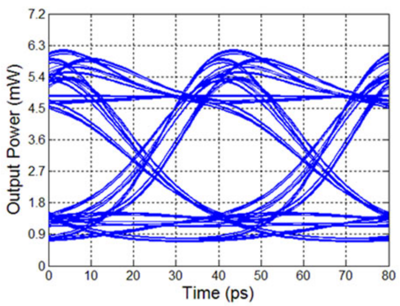
$T_s$=23$^o$C

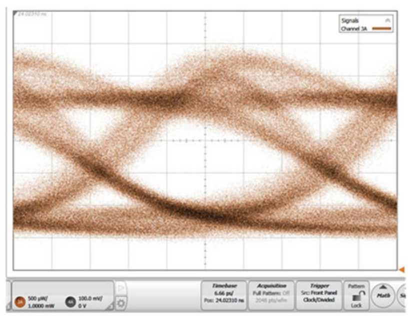
$I_b$=4mA



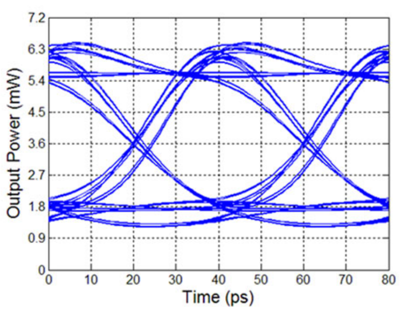



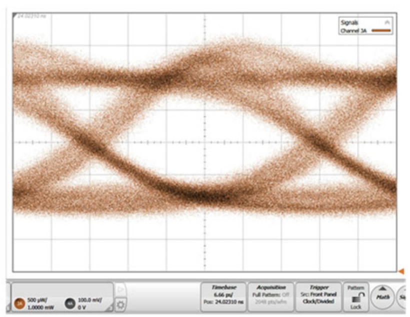
$I_b$=5mA



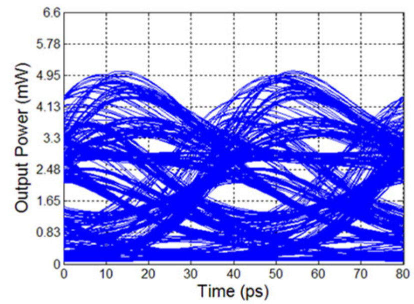
$I_b$=6mA

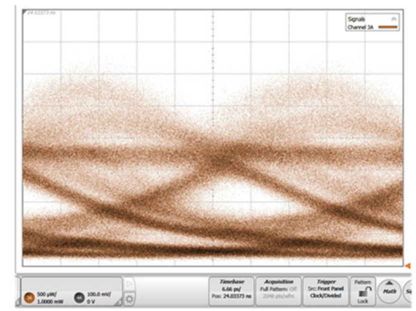


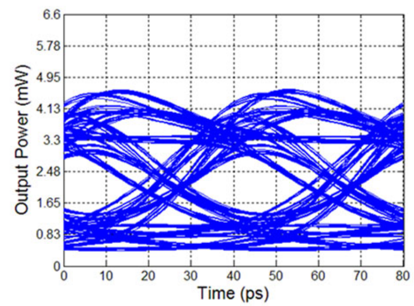
$T_s$=80$^o$C

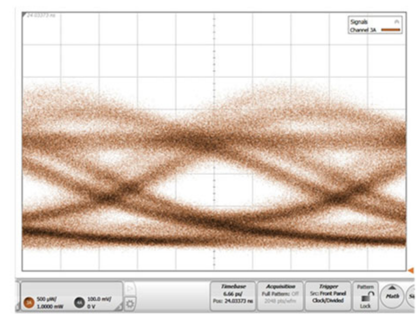
$I_b$=4mA



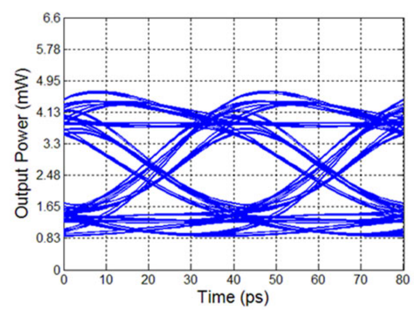



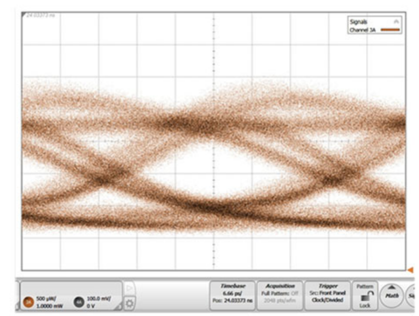
$I_b$=5mA



$I_b$=6mA

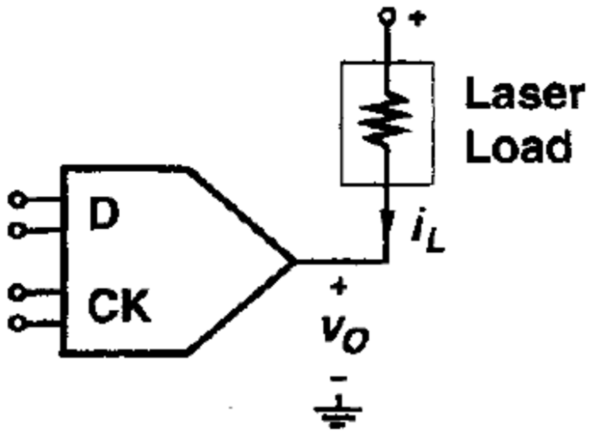


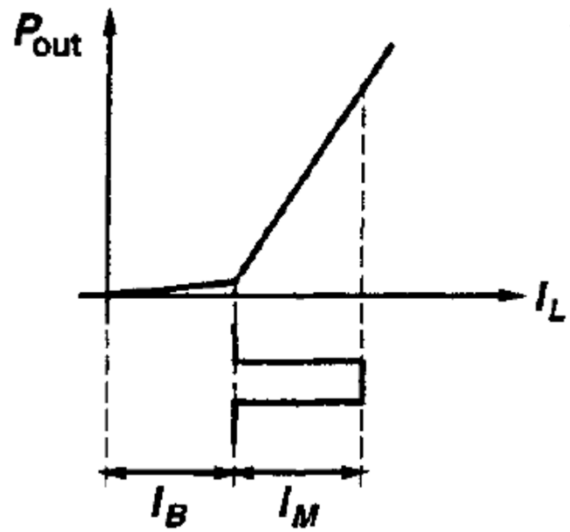



# VCSEL Performance Issues

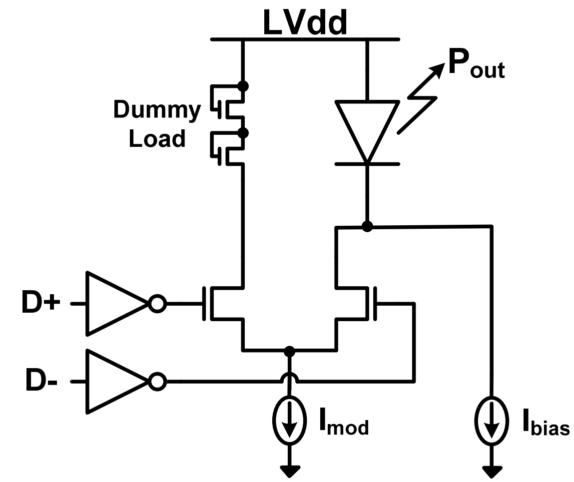
- Threshold Current
  - Reduced with smaller devices, better electron/photon confinement (quantum wells)
- Bias Dependent Frequency Response
  - Proportional to Sqrt(Ibias)
  - Low damping factor causes relaxation oscillations in step response
- Turn-On Delay
  - Leads to data-dependent jitter if biased below threshold
- Chirp
  - Direct amplitude modulation also modulates the frequency of the optical carrier
  - Leads to dispersion in optical fiber
  - Reason why most long-haul systems use external modulation

# Laser Drivers



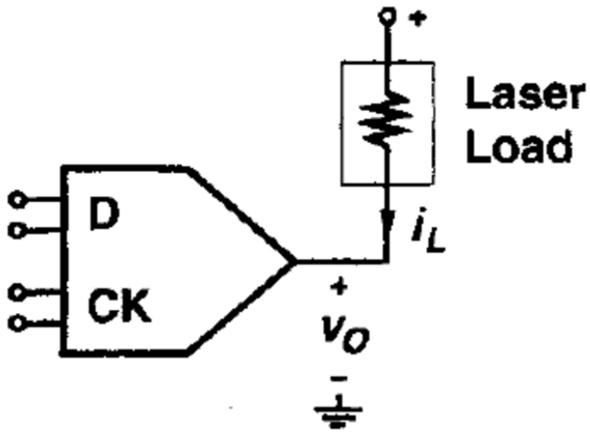

**Current-Mode VCSEL Driver**

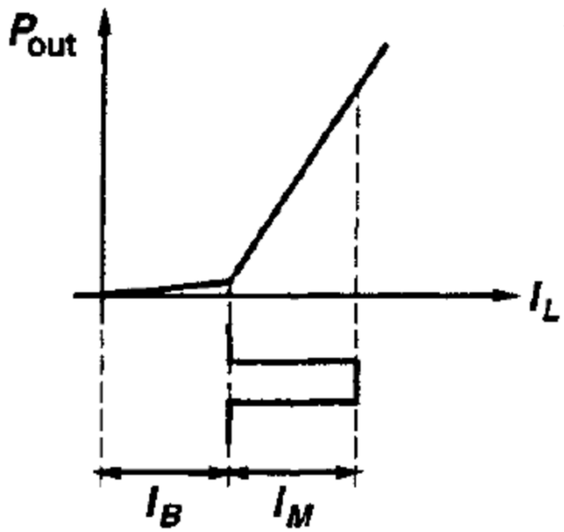



- Current-mode drivers are often used due to the laser's linear L-I relationship

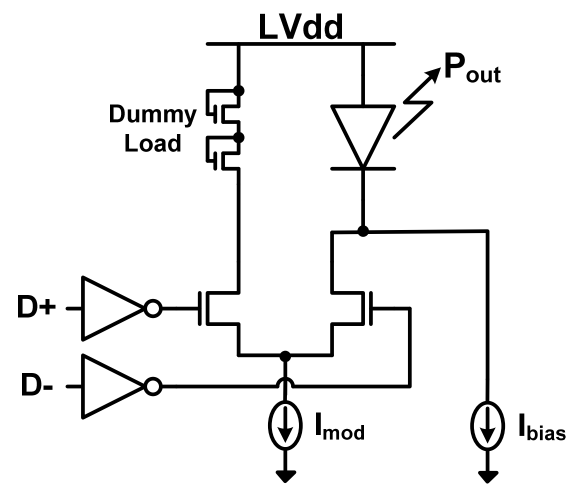
- In addition to the high-speed modulation current $I_M$, laser drivers must also supply a bias current $I_B$ to ensure a minimum frequency response and/or eliminate turn-on delay

# Laser Drivers




**Current-Mode VCSEL Driver**




- The total laser current depends on whether the high-speed modulation current is DC- or AC-coupled
- DC-coupled case

  The bias current is the 0 - level current

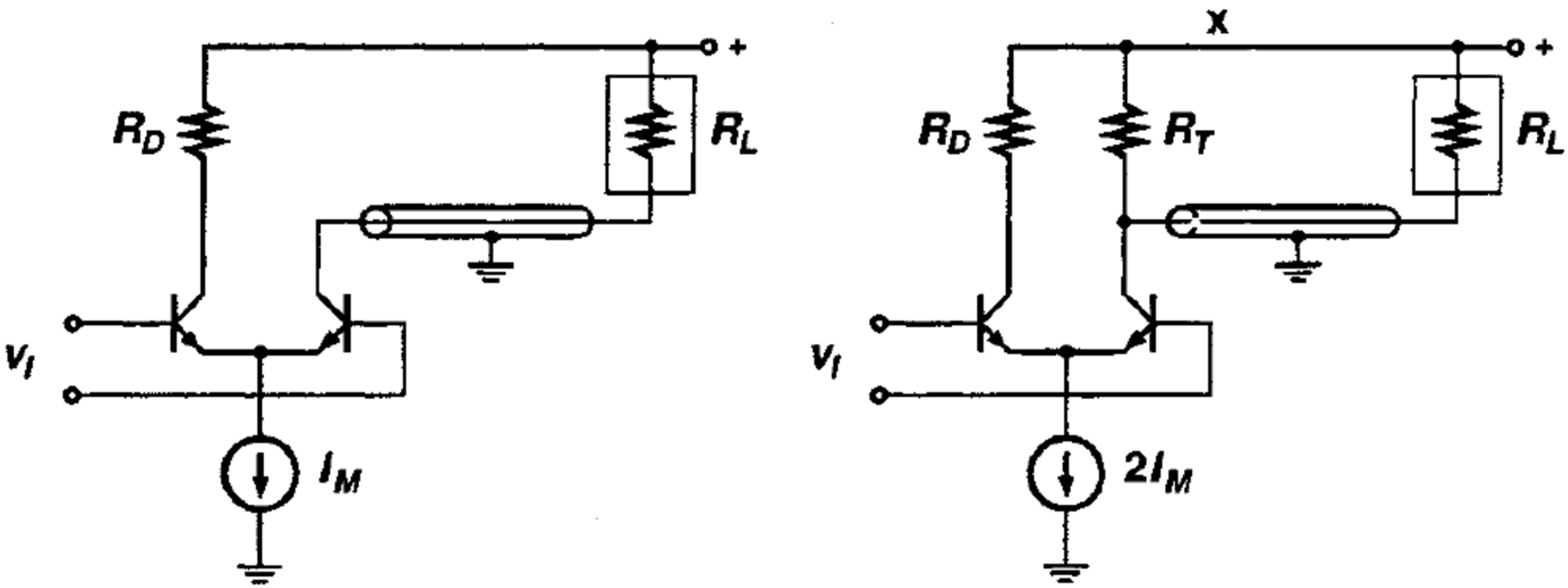
$$I_{L,0} = I_B \qquad I_{L,1} = I_B + I_M$$

- AC-coupled case

  The bias current is the average current

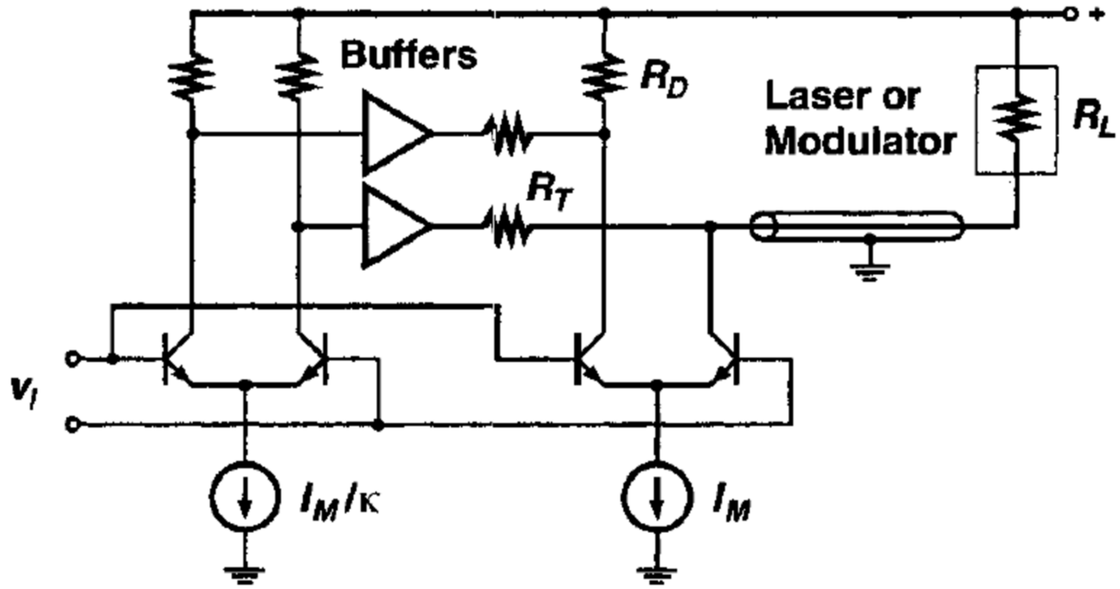
$$I_{L,0} = I_B - \frac{I_M}{2} \qquad I_{L,1} = I_B + \frac{I_M}{2}$$

# Termination Strategies




- The laser interface with the driver determines whether double or "back" termination is necessary
- Reflections from bondwires and any laser/transmission-line mismatch can degrade high-speed performace
- Driver on-die termination improves this at a power cost

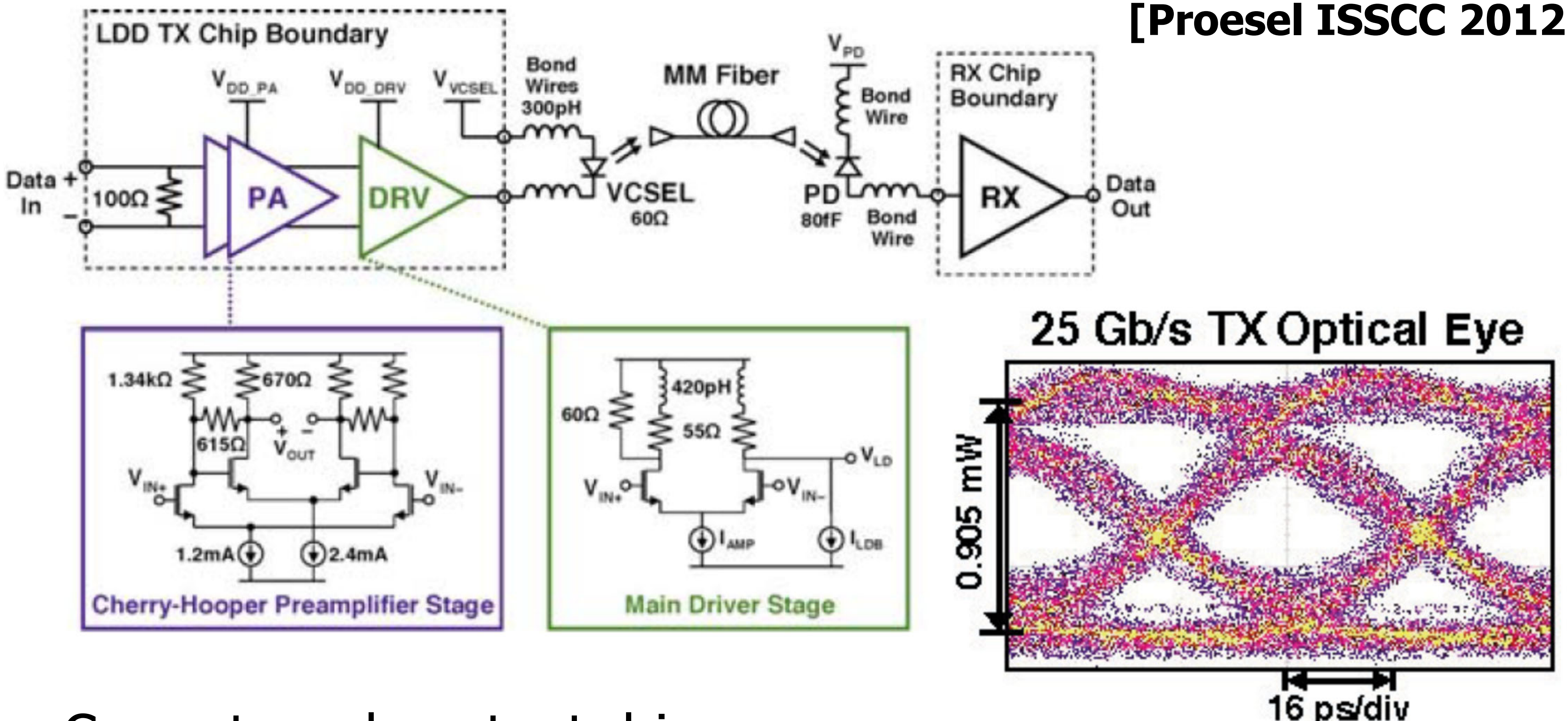
# Active Back Termination




- While not a major issue for relatively low-power VCSELs, the lost current with on-die driver termination is a concern for high-power (long-haul) lasers
- This motivates the use of active back termination circuitry where the termination resistor is connected to an AC voltage generated by a replica stage
- Ideally, without reflections, no voltage drop is across $R_T$

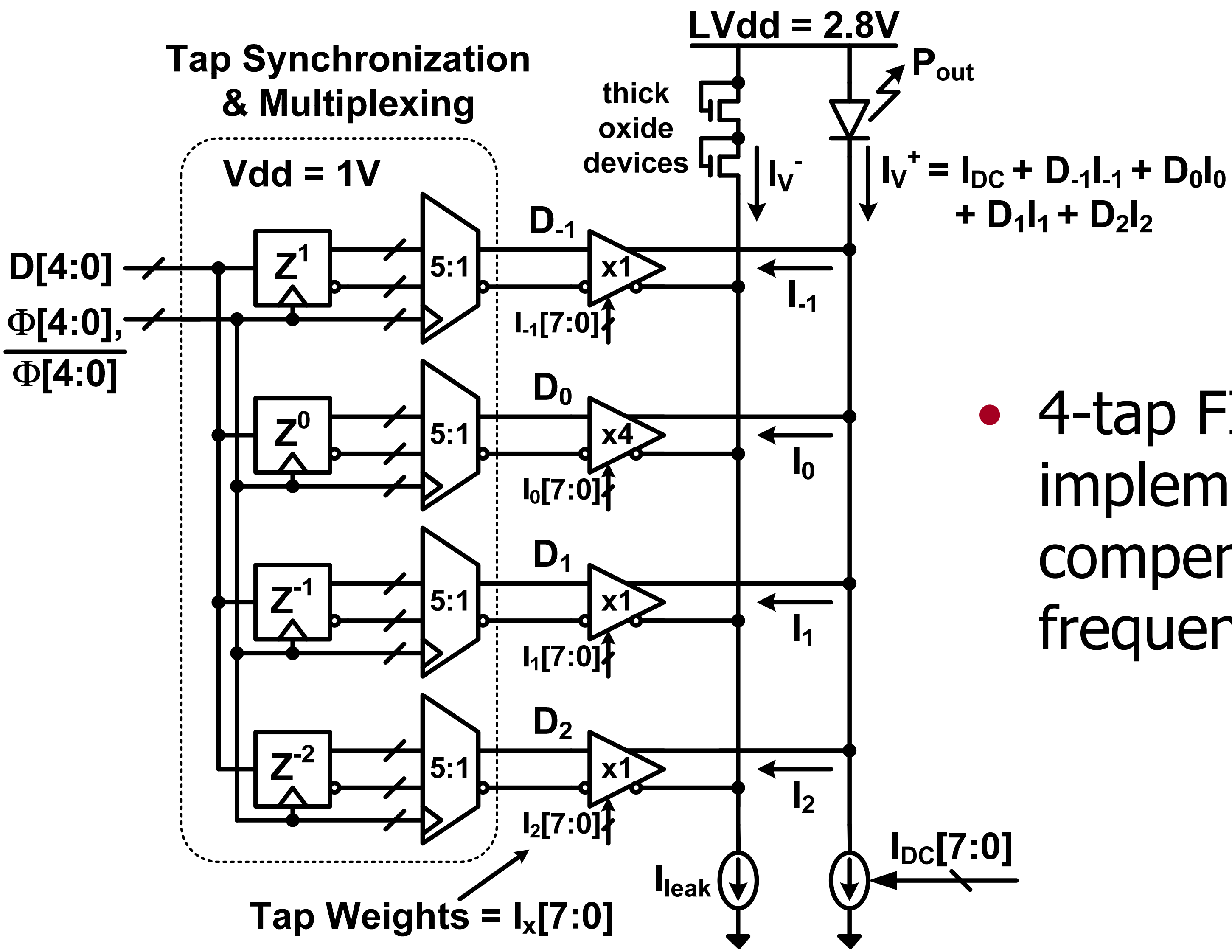
# 25Gb/s VCSEL Link

[Proesel ISSCC 2012]




- Current-mode output driver
- Bandwidth extension achieved with on-die shunt-peaking termination in the output stage and with Cherry-Hooper preamplifier stage

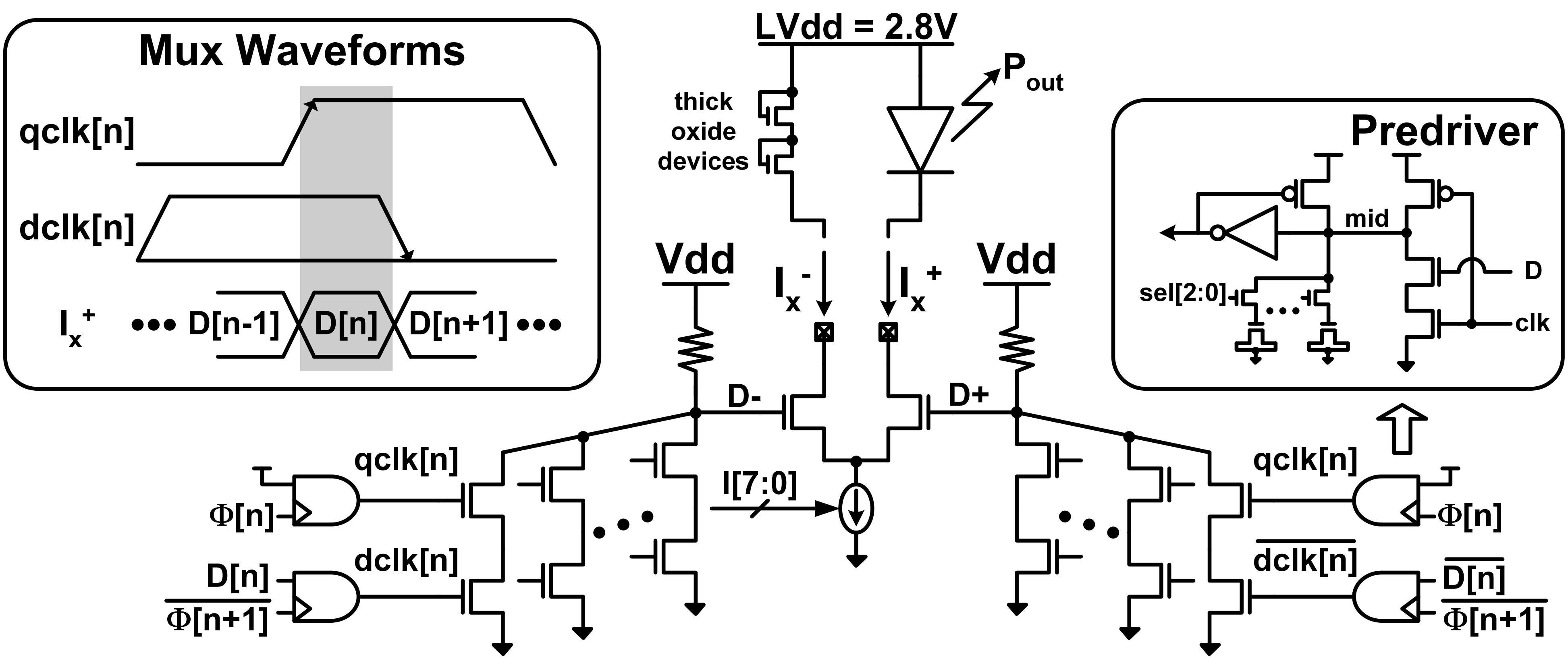
# Multiplexing FIR Output Driver




- 4-tap FIR filter implemented in driver to compensate for VCSEL frequency response

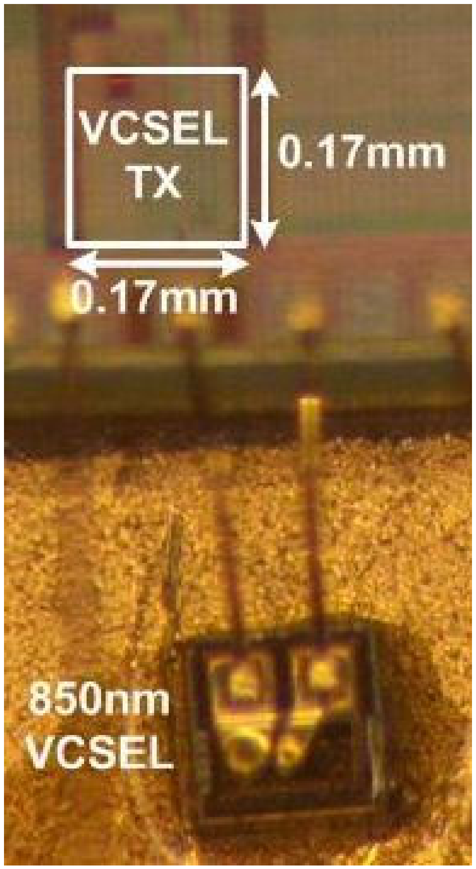
S. Palermo and M. Horowitz, "High-Speed Transmitters in 90nm CMOS for High-Density Optical Interconnects," *ESSCIRC*, 2006.

# Tap Mux & Output Stage

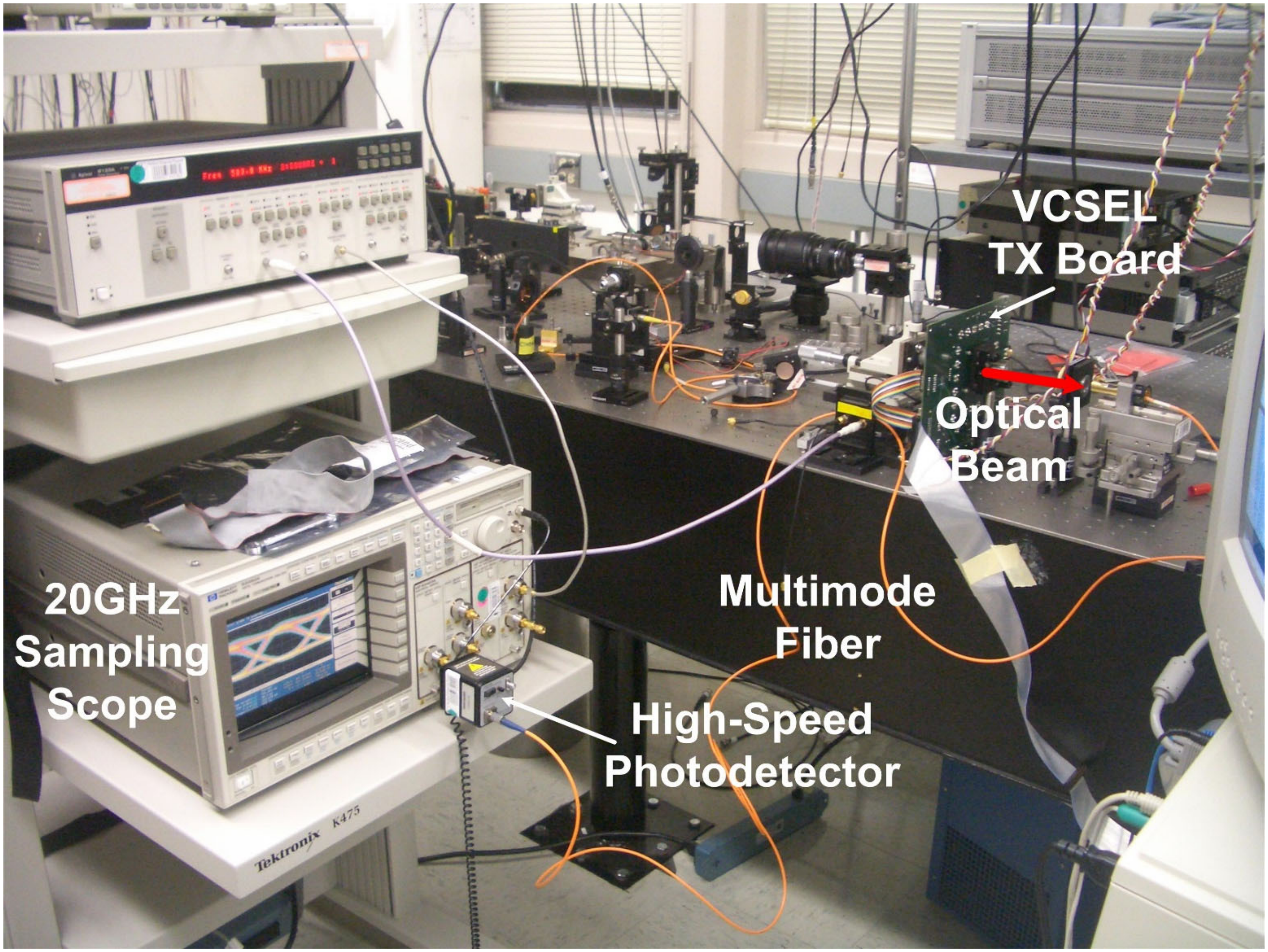



- 5:1 multiplexing predriver uses 5 pairs of complementary clock phases spaced by a bit time
- Tunable delay predriver compensates for static phase offsets and duty cycle error

# VCSEL TX Optical Testing




Wirebonded
10Gb/s VCSEL



# VCSEL 16Gb/s Optical Eye Diagrams

$I_{avg}$=6.2mA, ER=3dB

No Equalization

$I_{DC}$ = 4.37mA

$I_{MOD}$ = 3.66mA

w/ Equalization

$I_{DC}$ = 3.48mA

$I_{-1}$ = -0.70mA

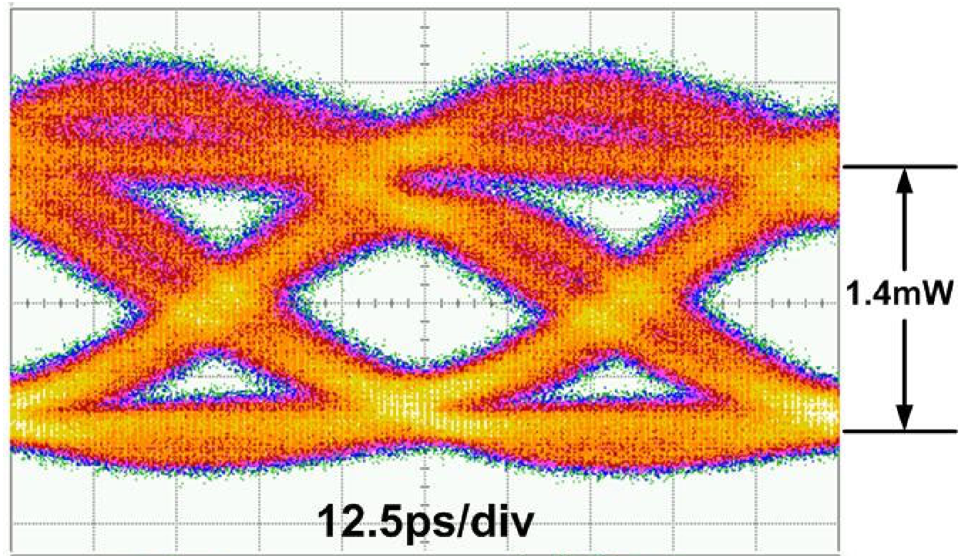
$I_0$ = 4.36mA

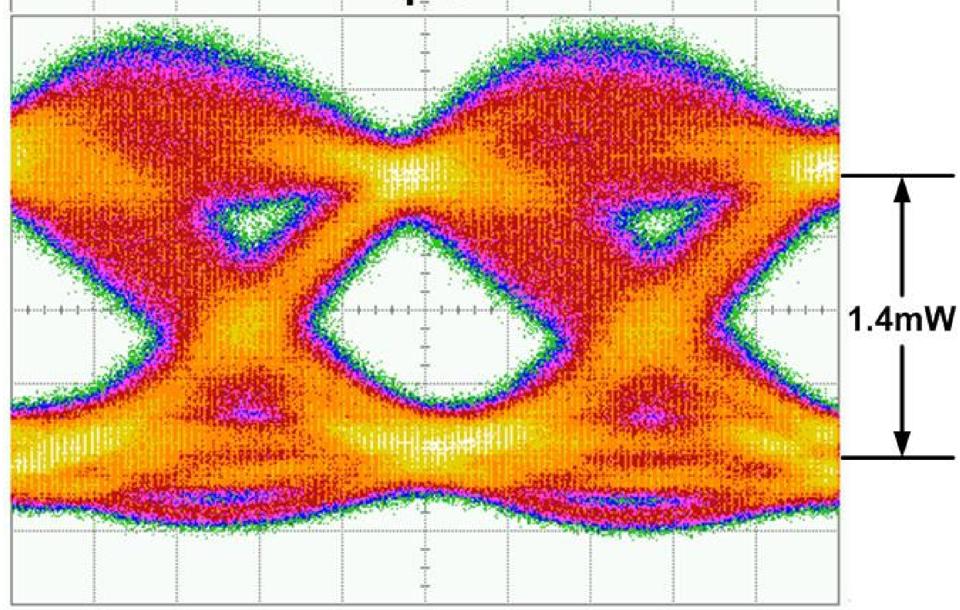
$I_1$ = -0.19mA

$I_2$ = 0.19mA

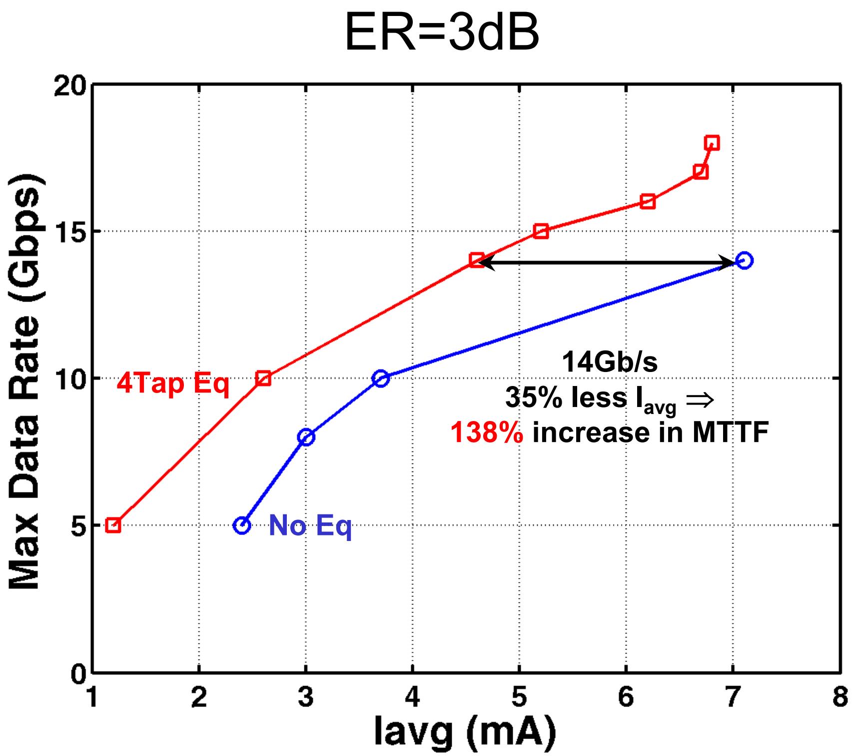
Equalization increases vertical eye opening

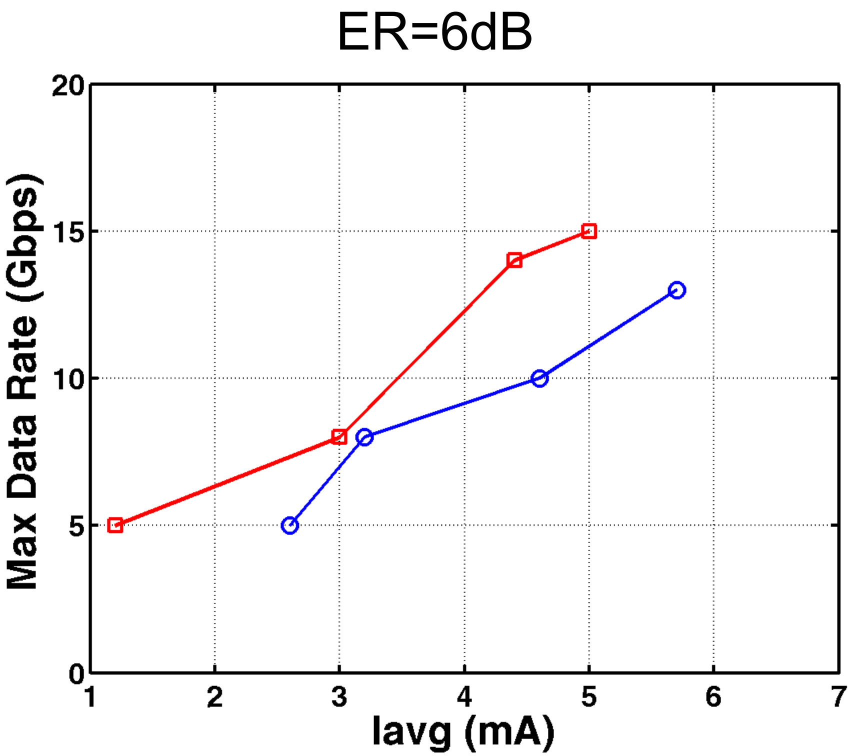
45% at 16Gb/s



# Equalization Performance




- Maximum data rate vs Average current
  - Min 80% eye opening & <40% overshoot
- Equalization allows lower average current for a given data rate
- Linear equalizer limited by VCSEL nonlinearity

# PAM2 VCSEL Driver w/ 2-Tap Nonlinear FFE

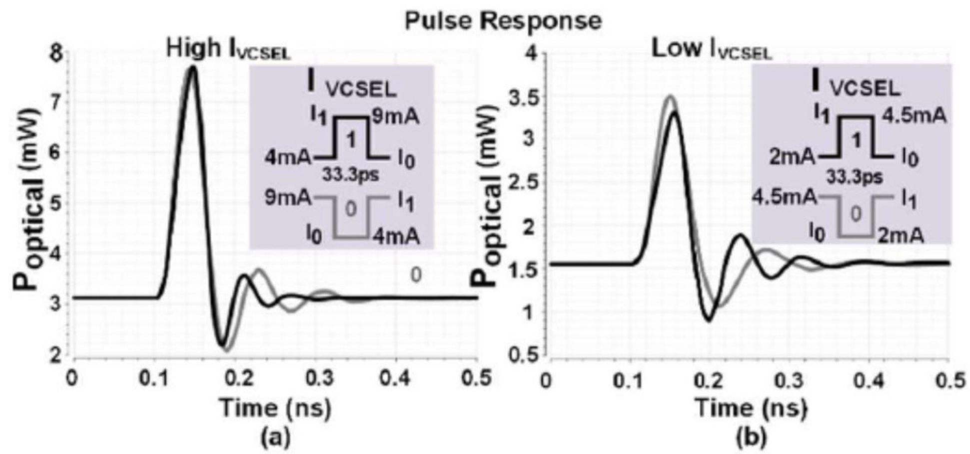
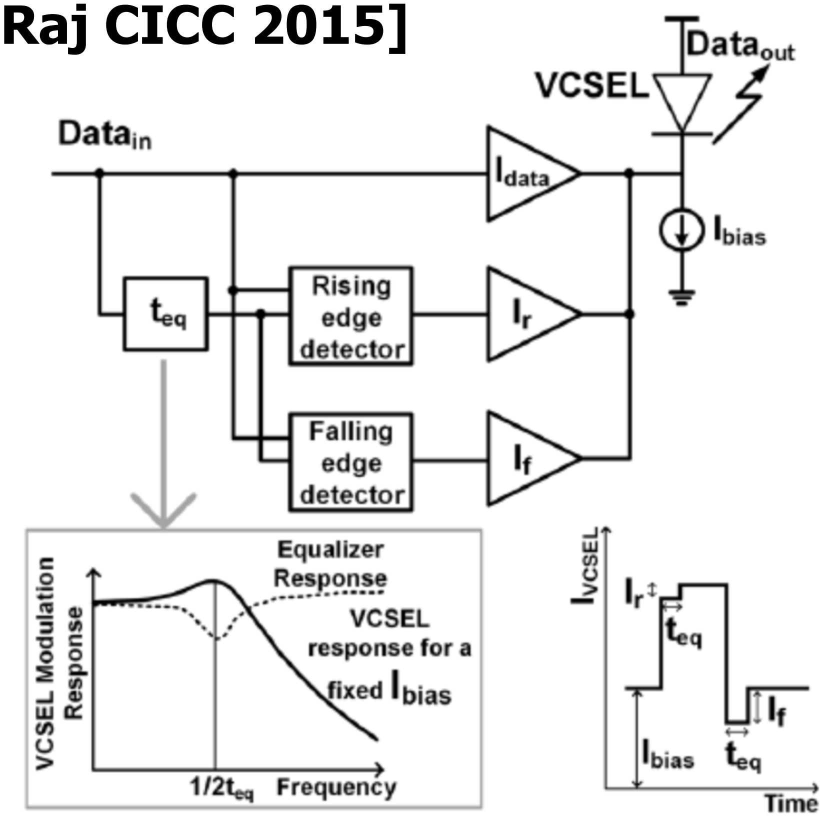



Fig. 2. VCSEL pulse responses for (a) high and (b) low IVCSEL.

[Raj CICC 2015]




- VCSEL's bias-dependent frequency response results in nonlinear transient pulse responses
- A 2-tap non-linear equalizer with different equalization taps for high and low pulses provides performance improvement

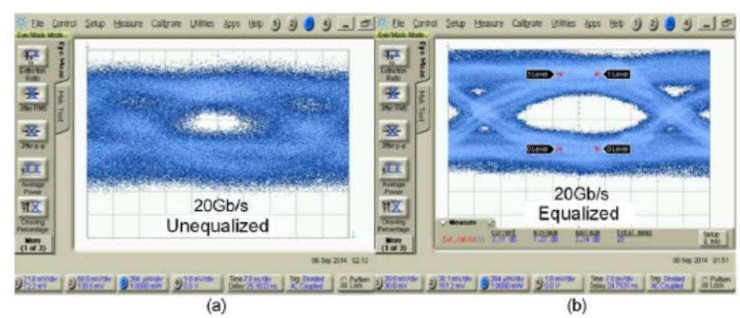
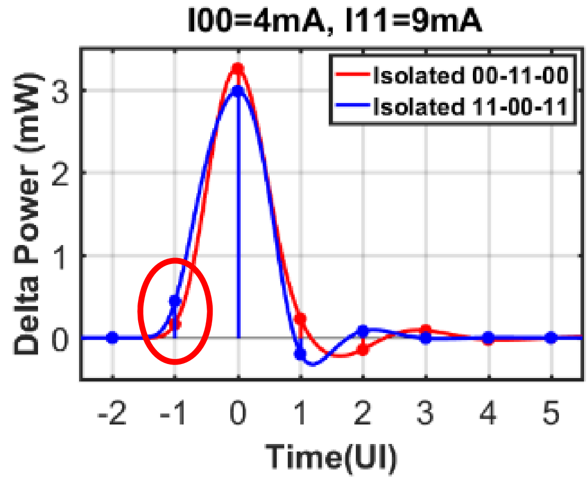
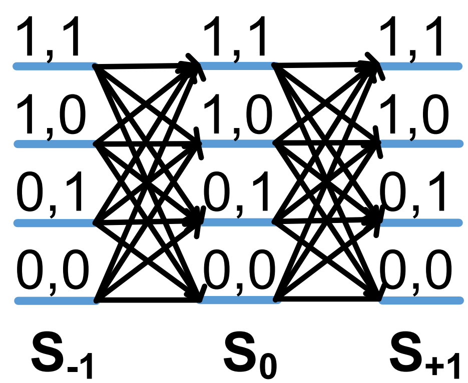



Fig. 8 Measured optical eye-diagram for PRBS-15 data at 20Gb/s. (a) Unequalized (b) Equalized.

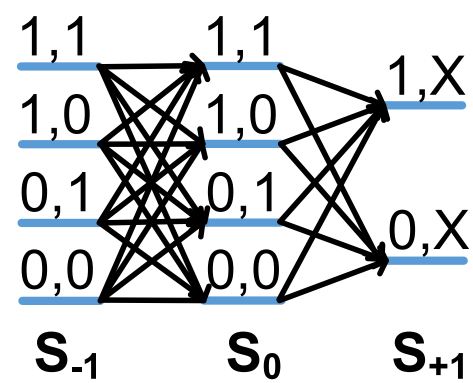
# PAM4 VCSEL Driver w/ 2.5-Tap Nonlinear FFE

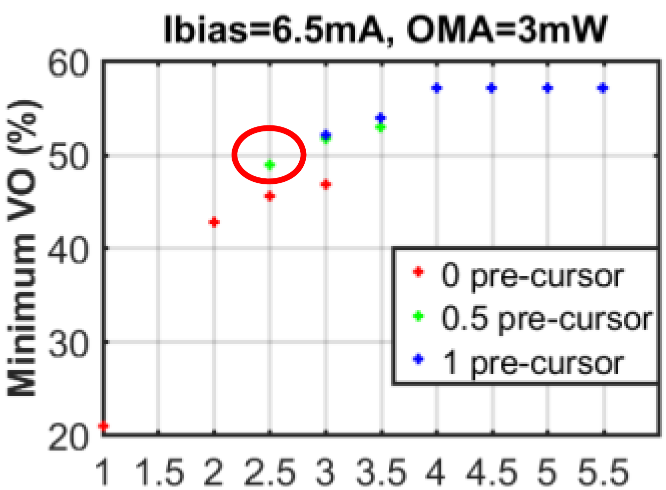


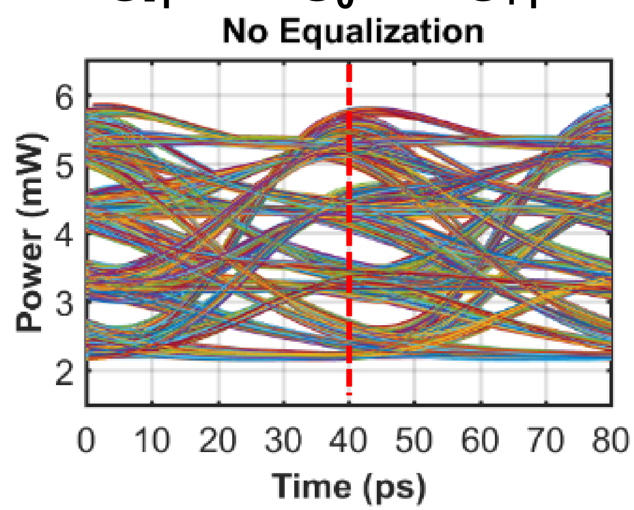

**3-tap equalizer**

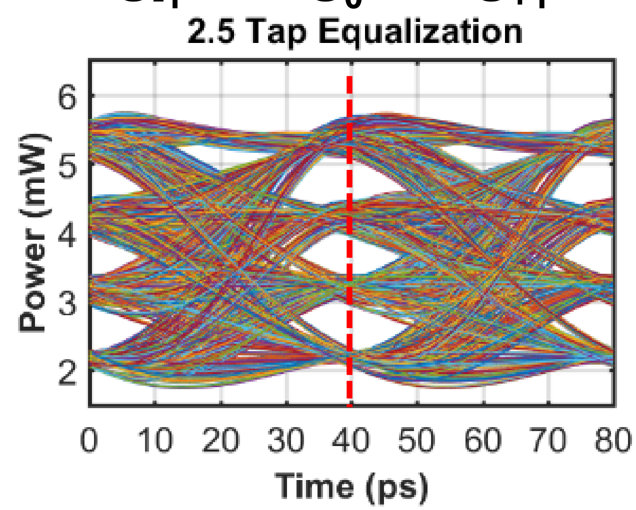



**2.5-tap equalizer with the pre-cursor weight only a function of the MSB**



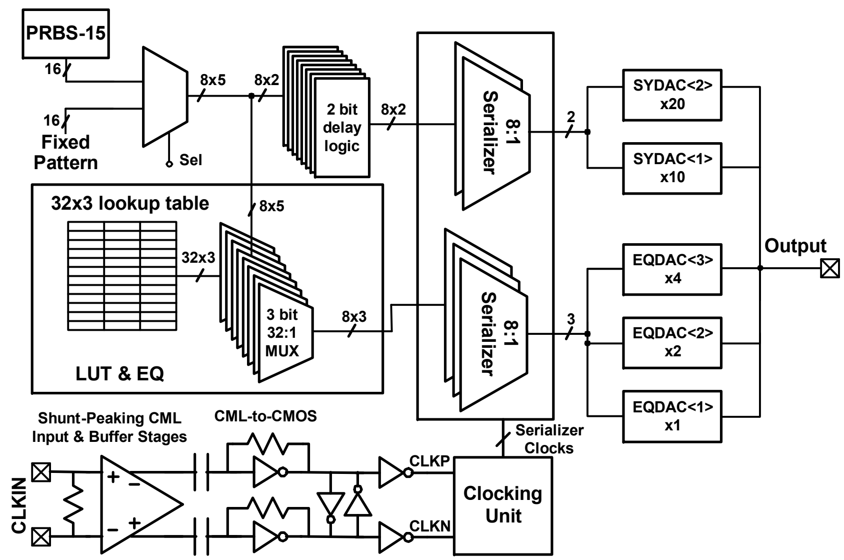



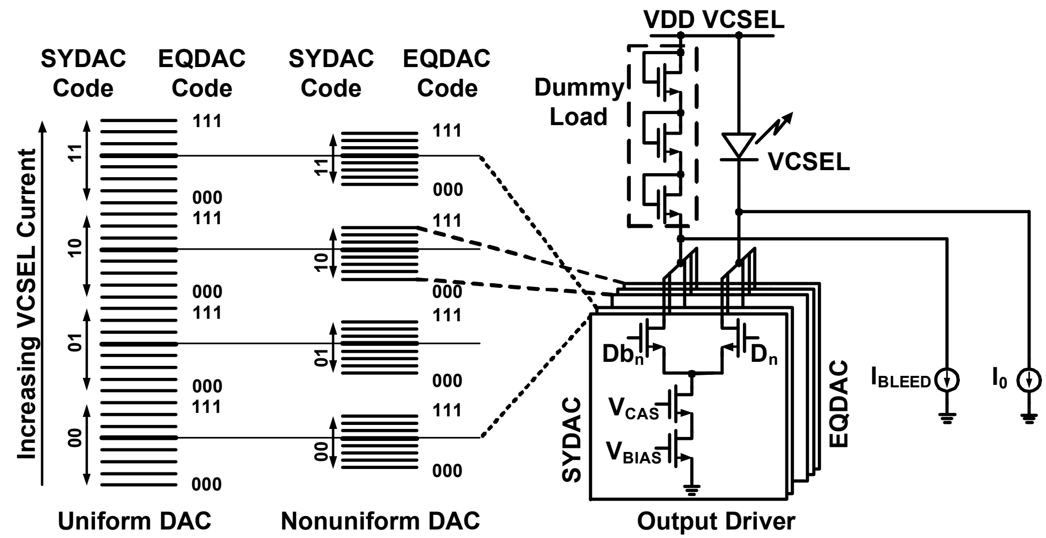

- A 2.5-tap nonlinear equalizer, with the first pre-cursor weight only dependent on the MSB, is a good compromise between complexity and performance

# Serializing VCSEL TX & Output Stage

## Serializing VCSEL TX



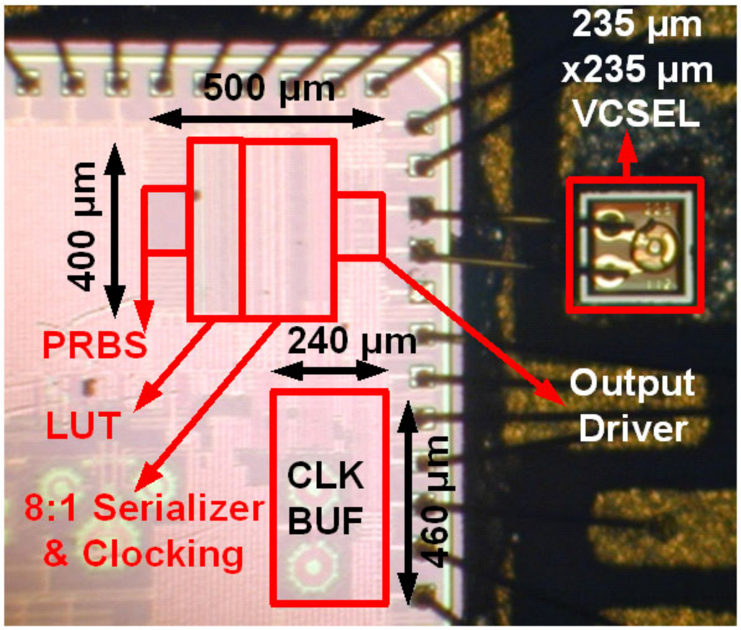

## 5-b Non-Uniform Current DAC Driver



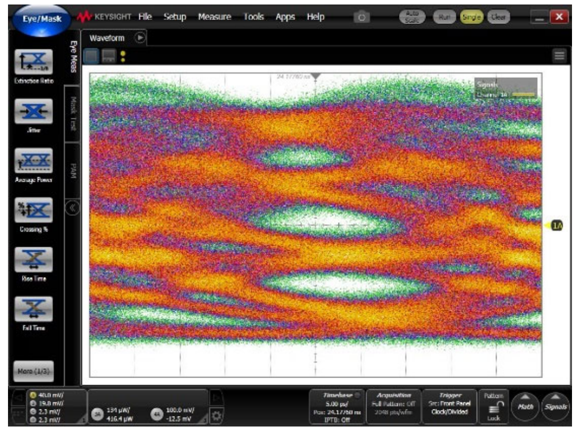

- VCSEL transmitter serializes 16 bits or 8 PAM-4 symbols
- Output stage is a 5-bit non-uniform current-mode DAC
  - MSB and MSB-1 set the main PAM-4 symbol levels
  - 3 LSB currents implement the 2.5-tap equalizer with the symbol pattern selecting the weighting from the 32X3 LUT

# 50Gb/s PAM4 Experimental Results

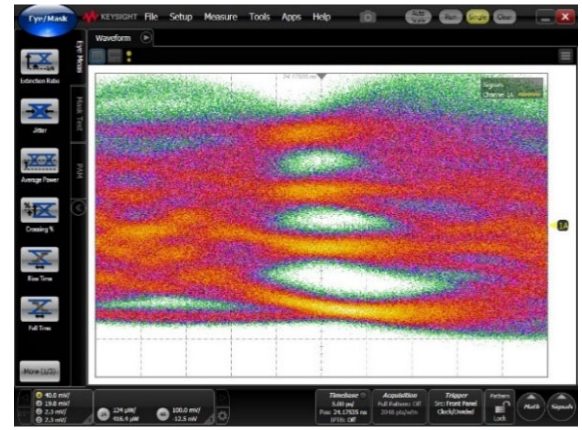
**[Tyagi PTL 2018]**



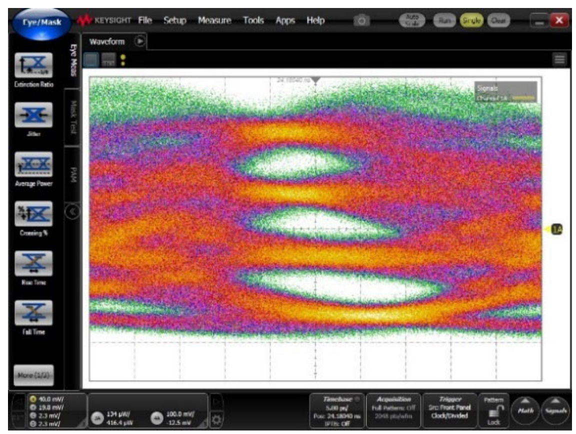

**No Equalization**



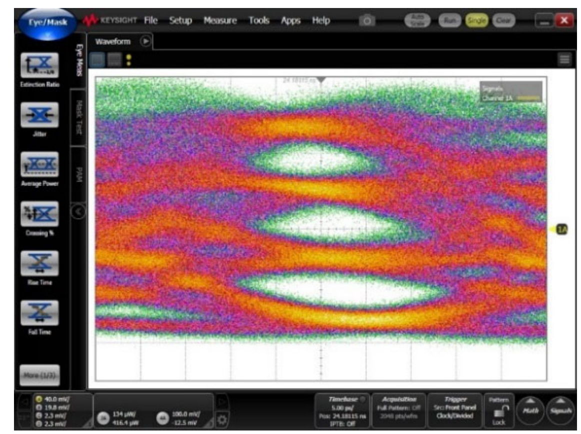
**2-Tap Linear**



**2.5-Tap Linear**



**2.5-Tap Nonlinear**



- Core transmitter area is 0.2mm$^2$
- 2.5 tap nonlinear equalizer improves eye height and timing alignment of the 3 PAM4 eyes

# Next Time

- Mach-Zehnder Modulator (MZM) TX