ECEN721: Optical Interconnects Circuits and Systems Spring 2024

Lecture 8: VCSEL TXs

Sam Palermo
Analog & Mixed-Signal Center
Texas A&M University

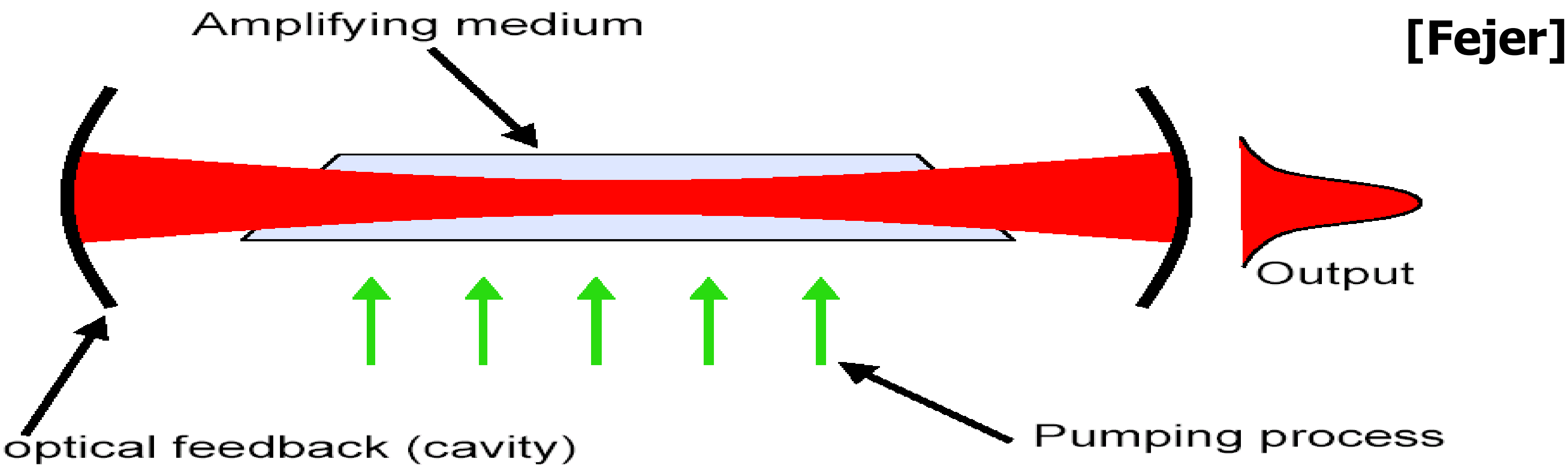
Announcements

- Exam 1 Mar 7
  - In class
  - One double-sided 8.5x11 notes page allowed
  - Bring your calculator
  - Covers through Lecture 6

- Homework 3 is due Mar 21

- Reading
  - Sackinger Chapter 8

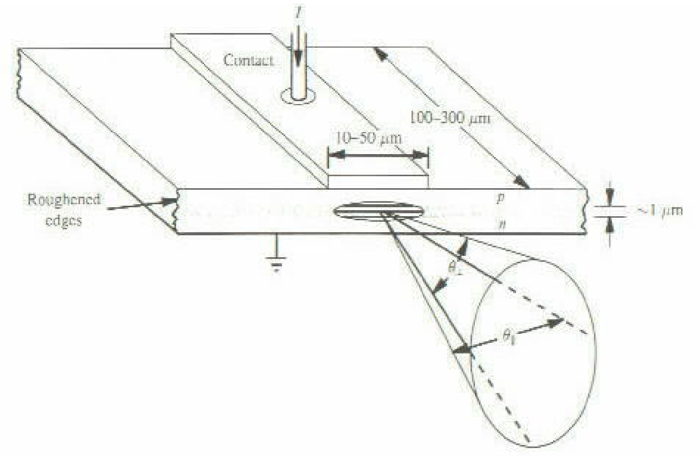
What is a Laser?

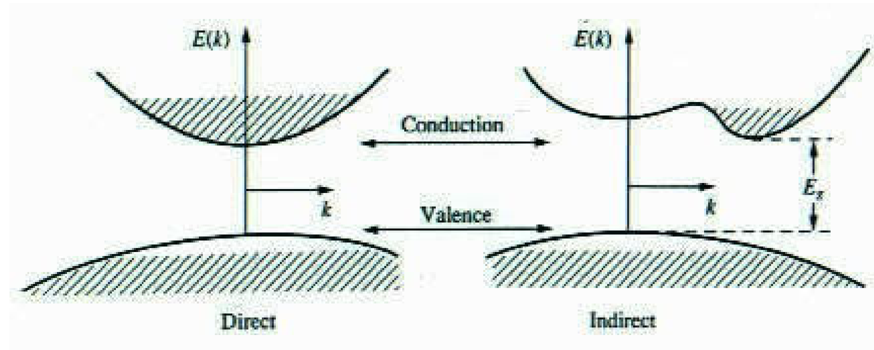


- **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation
- **L**ight **O**scillation by **S**timulated **E**mission of **R**adiation
- Lasers are optical oscillators that emit coherent light through the process of stimulated emission
- 3 Elements in all lasers
  - Amplifying Medium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

Semiconductor Diode Lasers

[Verdeyen]

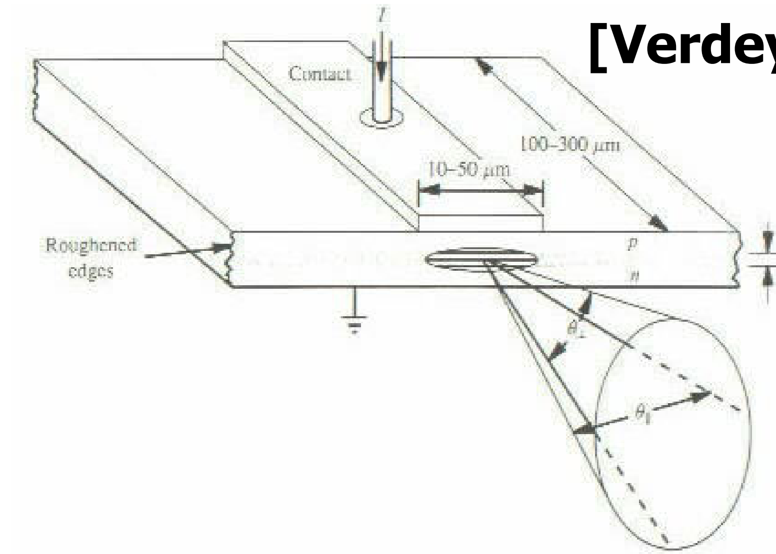




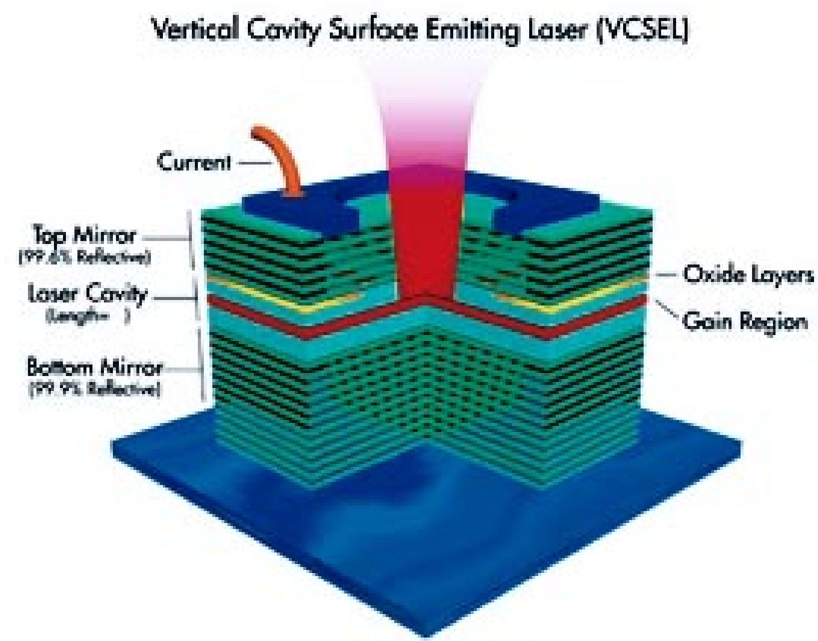
- Can be made with simple p-n junction
- Based on transitions between bands
  - Direct bandgap materials necessary
  - Si isn't ⇒ GaAs, InP
- Pumped electrically with current source
- Efficient device requires confinement of both carriers and photons
  - Leads to the use of heterostructures

Edge Emitters & VCSELs

[Verdeyen]

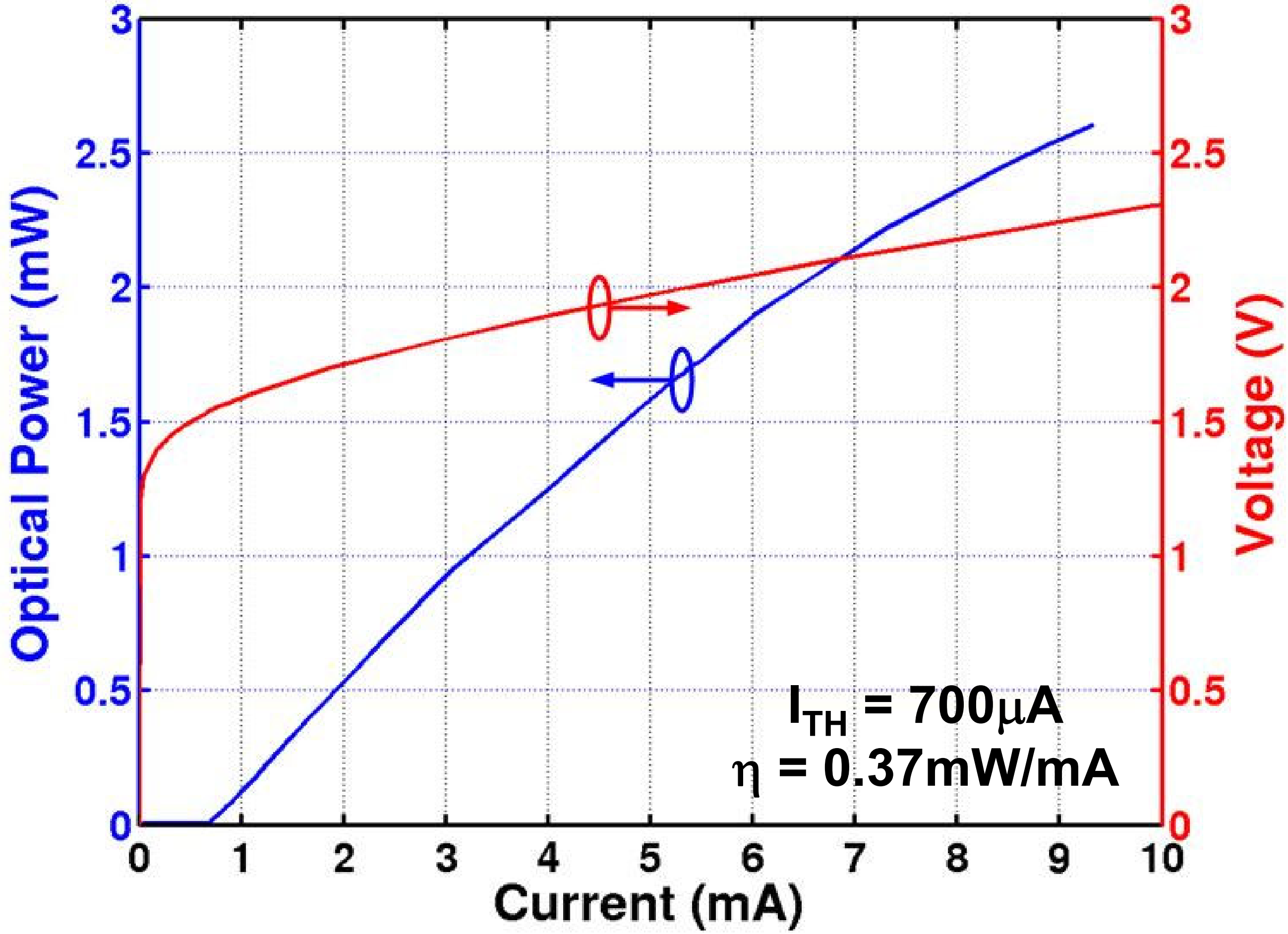


- Edge Emitters
  - Advantage
    - Historically easier to manufacture
  - Disadvantages
    - Emit light in an elliptical mode
    - Higher testing and packaging costs



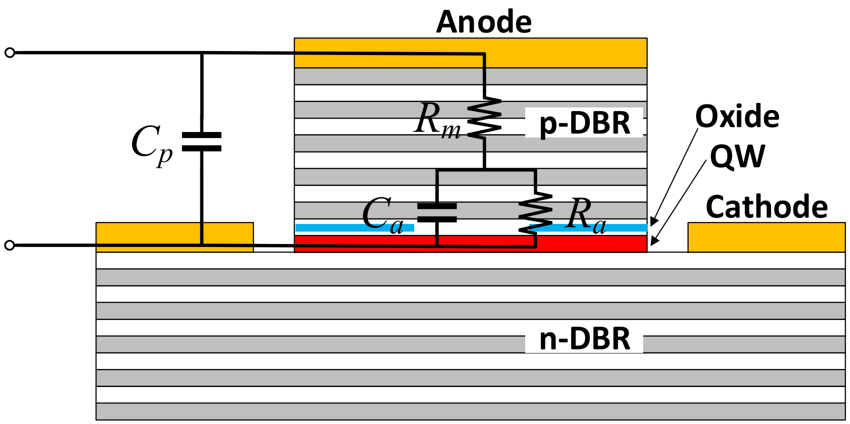
- VCSELs – Vertical Cavity Surface Emitting Lasers
  - Advantages
    - Can make 2-D arrays
    - Emit light in a circular output mode
    - Smaller device $\Rightarrow$ Lower operating currents
    - Lower testing and packaging costs
  - Disadvantage
    - Hard to manufacture due to growth of high reflective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

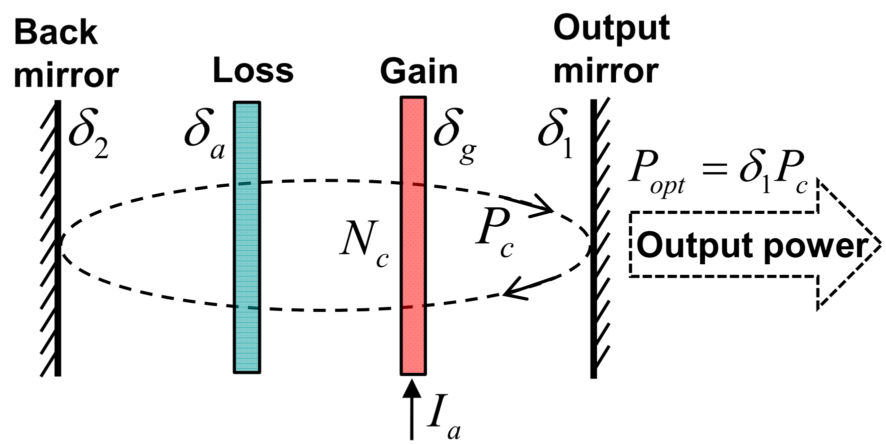
VCSEL Light-Current-Voltage (LIV) Curve



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

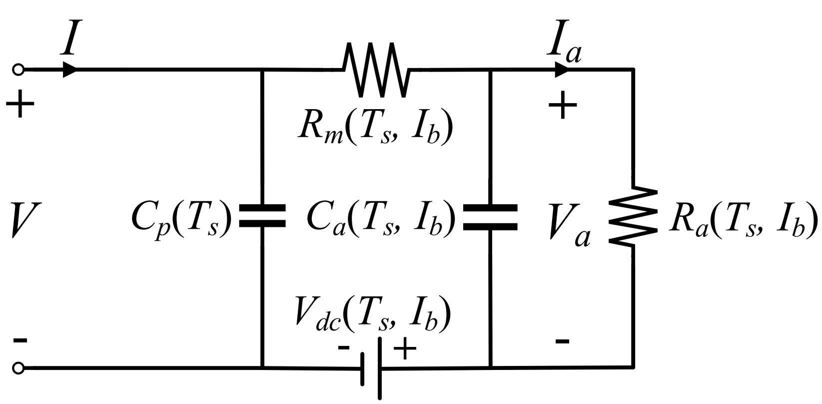
VCSEL Model

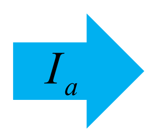




Electrical Input Stage

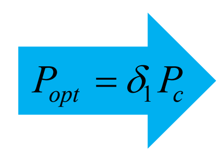
Optical Output Stage





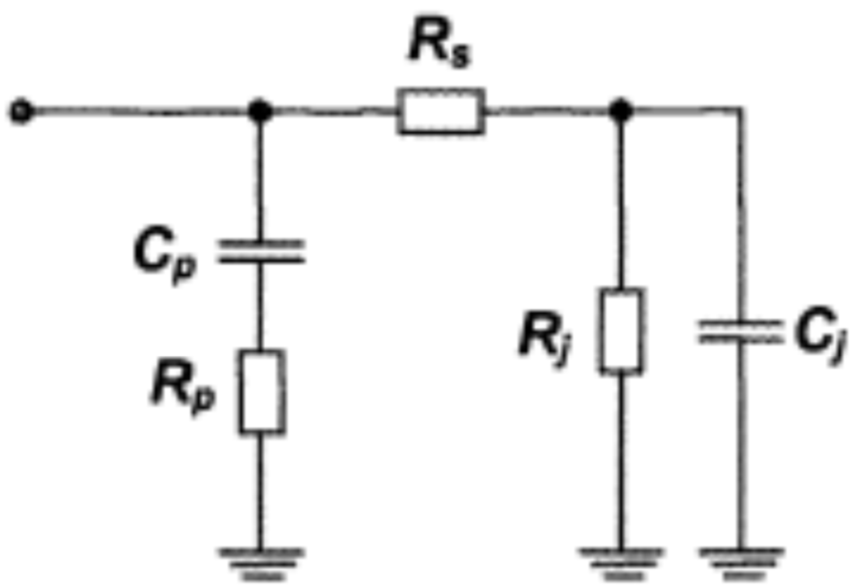
$$\frac{dN_c}{dt} = \frac{\eta_i(T)\cdot\left[I_a - I_{th}(T)\right]}{q} - \delta_g(T)\cdot\frac{P_c}{h\nu}$$

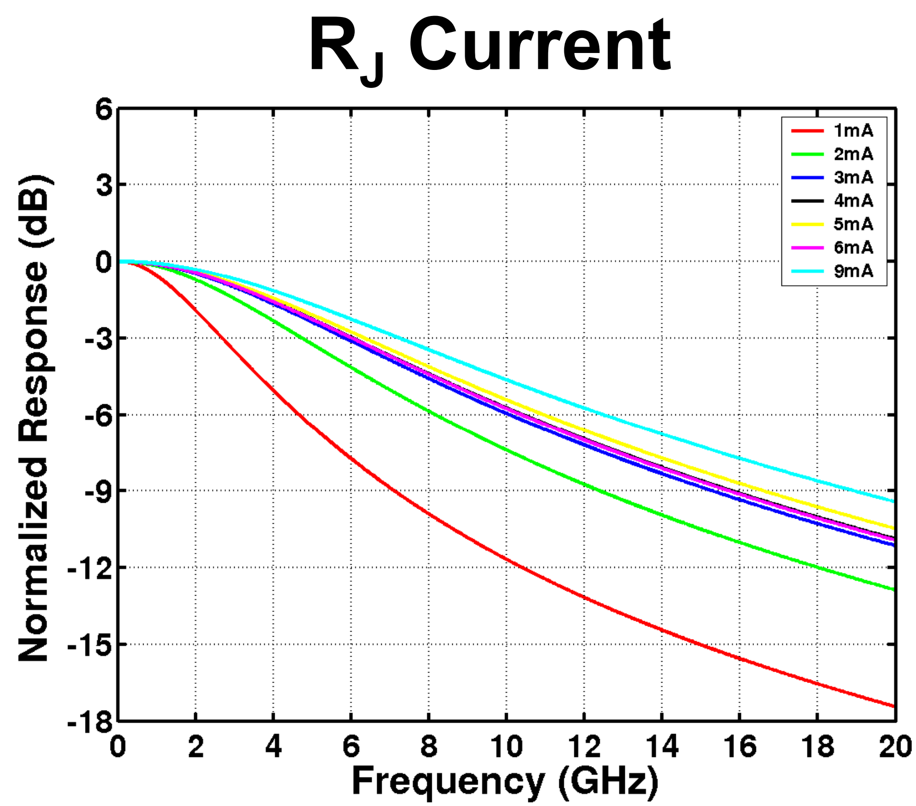
$$\frac{dP_c}{dt} = \left[\delta_g(T) - \delta_c\right]\cdot\frac{P_c}{\tau_c} + P_{sp}(T)$$



- 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 $I \geq 3mA$

Laser Rate Equations

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

Electron Density Rate Equation :

$$\frac{dN}{dt} = \frac{I}{qV} - \frac{N}{\tau_{sp}} - GNN_p$$

- $\frac{dN}{dt}$: Rate of electron density change
- $\frac{I}{qV}$: Injected electrons generation
- $\frac{N}{\tau_{sp}}$: Non-radiative & spontaneous emission recombination
- GNN_p: Stimulated emission recombination

$I =$ injected current

$V =$ cavity volume

$G =$ stimulated emission coefficient

$\beta_{sp} =$ spontaneous emission coefficient

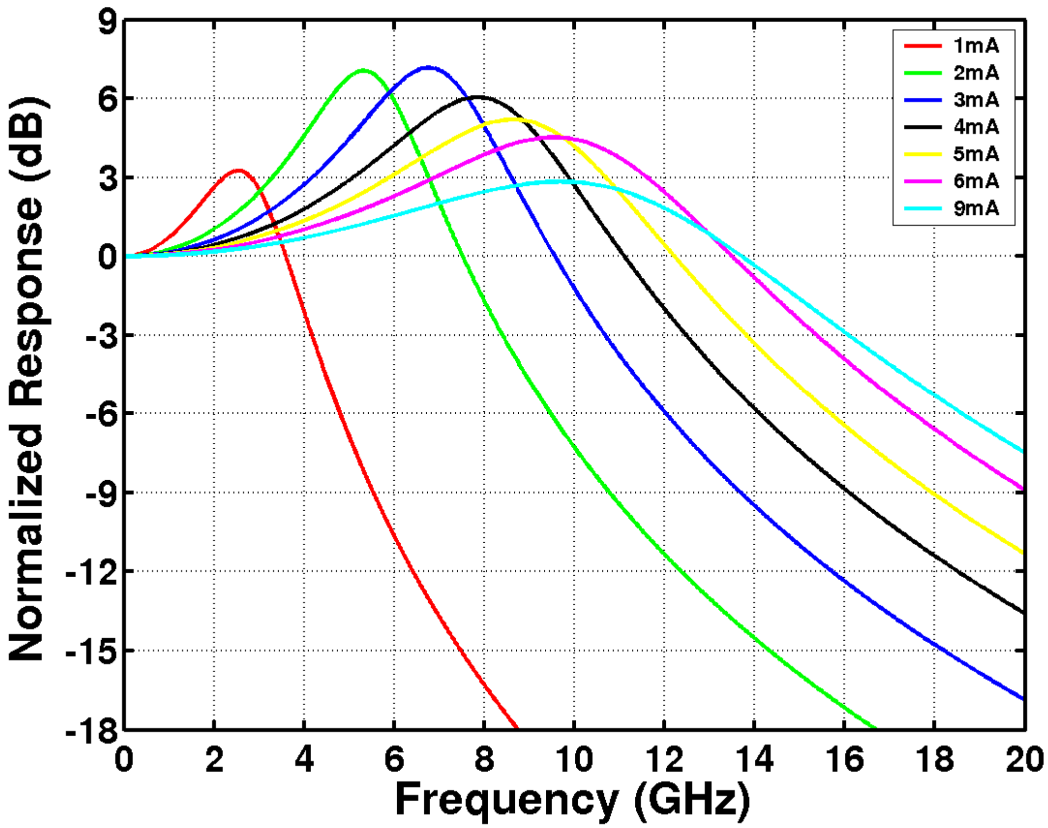
$\tau_p =$ photon lifetime

Photon Density Rate Equation :

$$\frac{dN_p}{dt} = GNN_p + \beta_{sp}\frac{N}{\tau_{sp}} - \frac{N_p}{\tau_p}$$

- $\frac{dN_p}{dt}$: Rate of photon density change
- GNN_p: Stimulated emission
- $\beta_{sp}\frac{N}{\tau_{sp}}$: Spontaneous emission
- $\frac{N_p}{\tau_p}$: Photons loss due to optical absorption and scattering

VCSEL Rate Equation Frequency Response



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

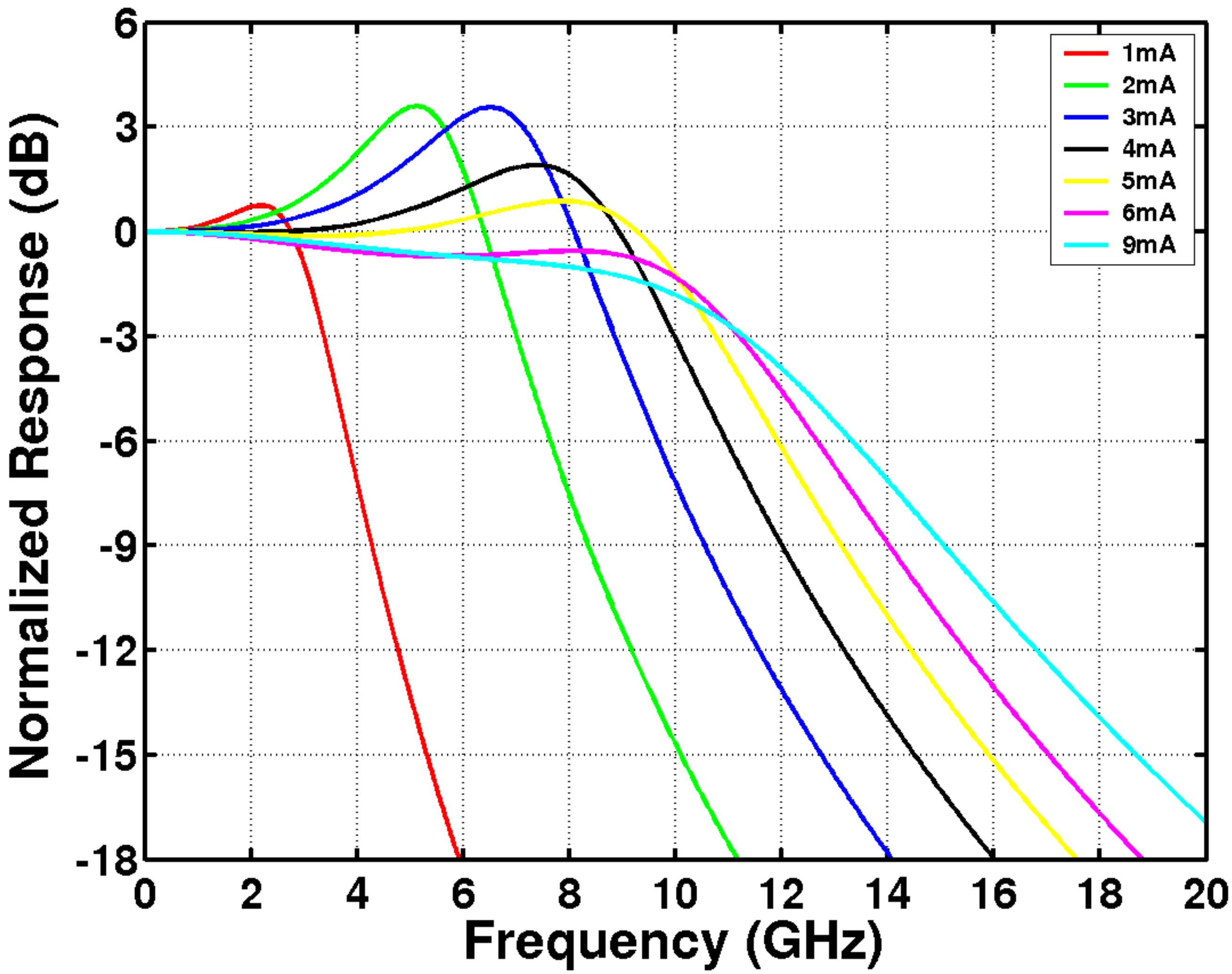
$$\zeta = \frac{GN_{pdc} + \frac{1}{\tau_{sp}}}{2\sqrt{\frac{GN_{pdc}}{\tau_p}}}$$

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

υ_g = group velocity

α_m = mirror loss coefficient

10Gb/s VCSEL Frequency Response



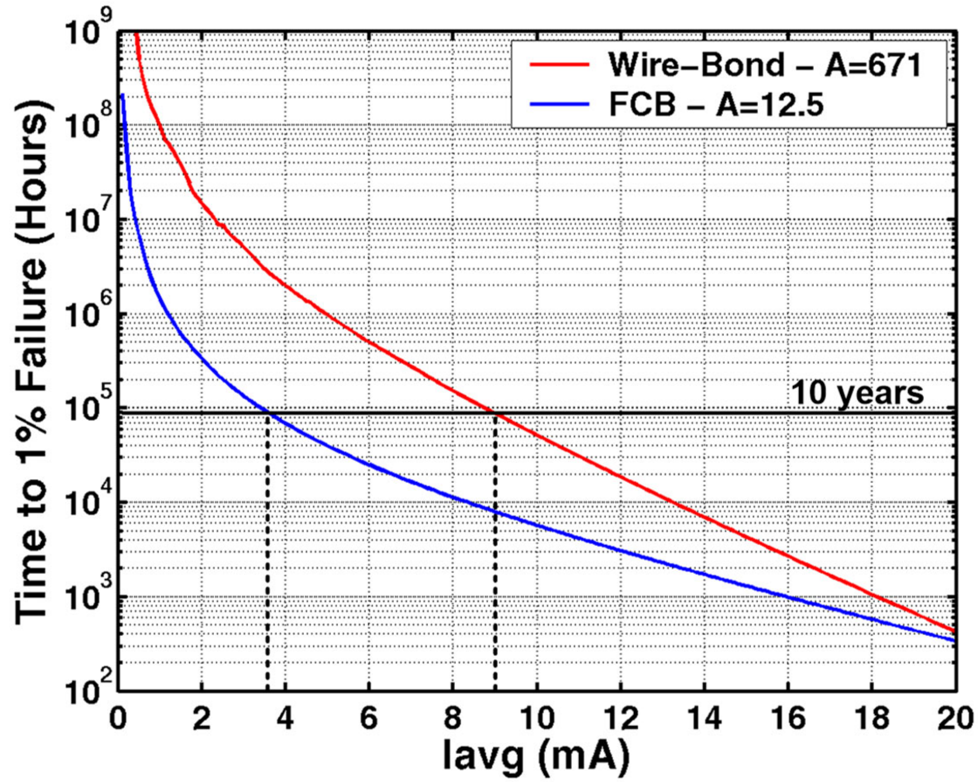
$$BW \propto \sqrt{I_{avg} - I_{TH}}$$

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

VCSEL Reliability

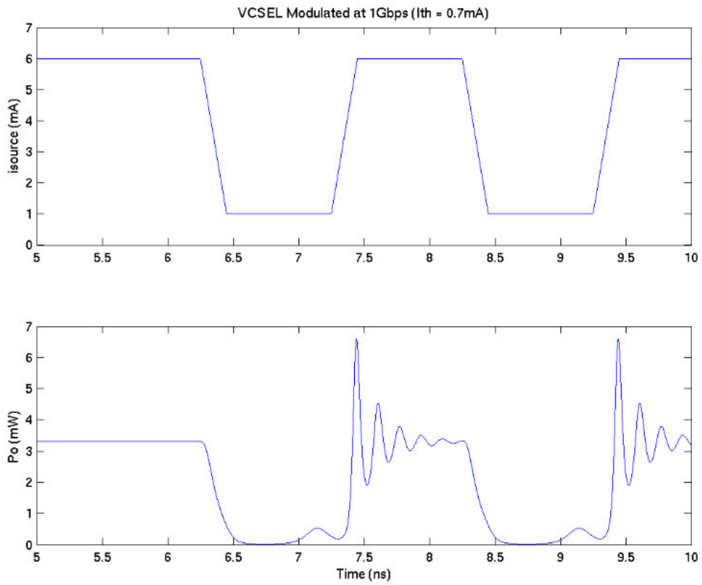
- Mean Time to Failure (MTTF) is inversely proportional to current density squared
- Failure time modeled with lognormal distribution
- Higher mechanical stress reduces flip-chip bond reliability
- Trade-off between reliability and bandwidth
  - $MTTF \propto \frac{1}{BW^4}$

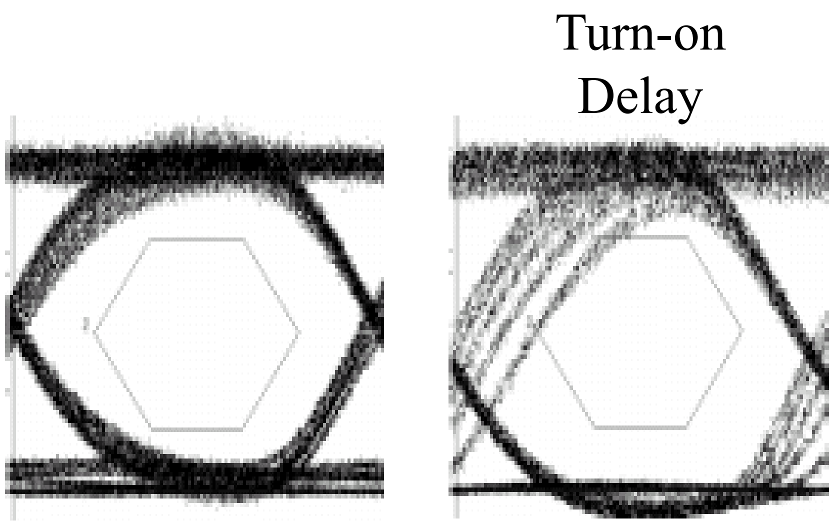
$$MTTF = \frac{A}{j^2} e^{\left(\frac{E_A}{k}\right)\left(\frac{1}{T_j} - \frac{1}{373}\right)}$$



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





[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 α is the *chirp parameter* or *linewidth enhancement factor*.

- The α 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 α values, implying that for a rising edge the laser will blue-shift (higher frequency/shorter λ) 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

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

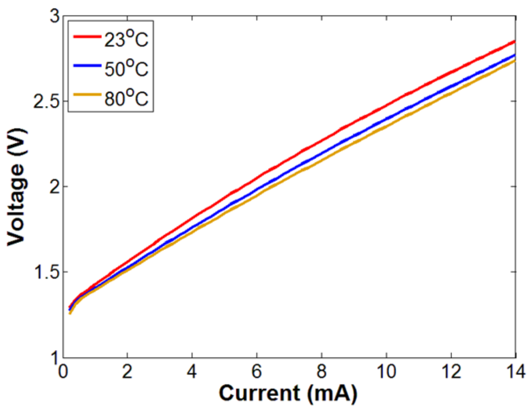
- This SNR is fine for digital NRZ signaling, but may be an issue for analog optical links for applications such as cable TV
- RIN noise does introduce an additional power penalty

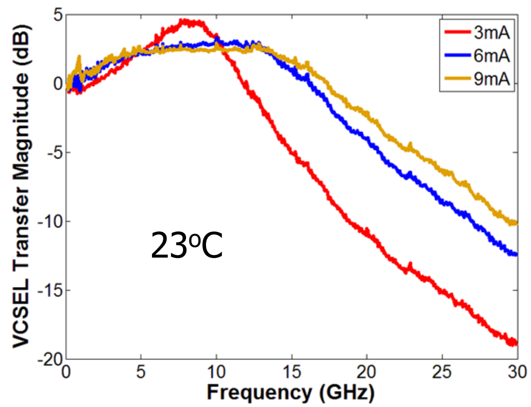
$$PP = \frac{1}{1 - Q^2 \cdot RIN \cdot BW_n}$$

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

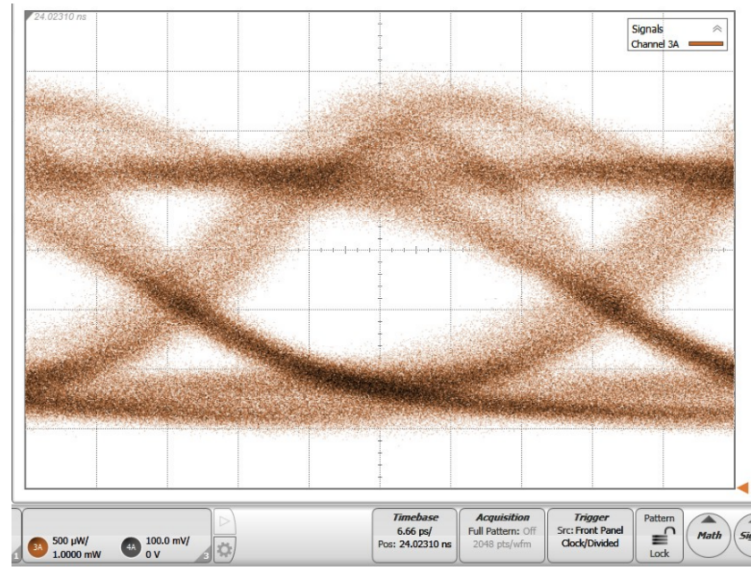
$$PP = \frac{1}{1-(7.035)^2\left(\frac{1}{3.16\times10^3}\right)} = 1.016 = 0.069dB$$

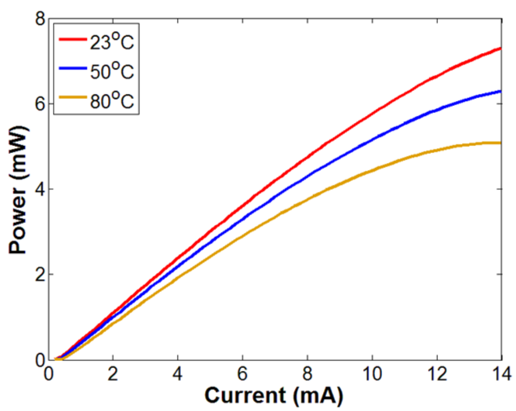
Temperature-Dependent Performance

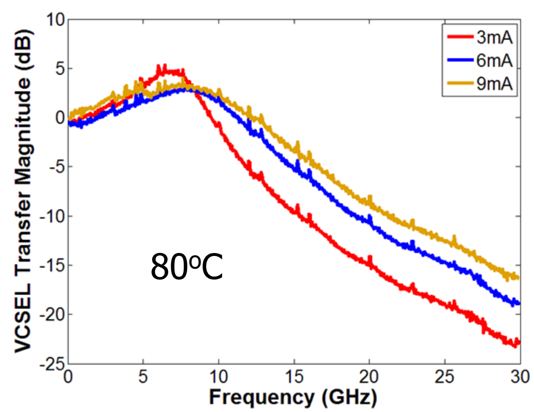




25Gb/s





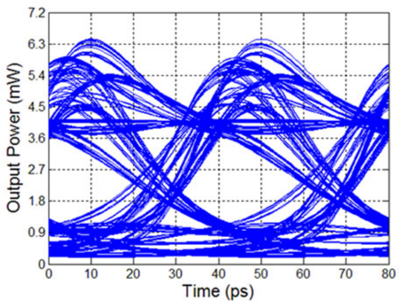


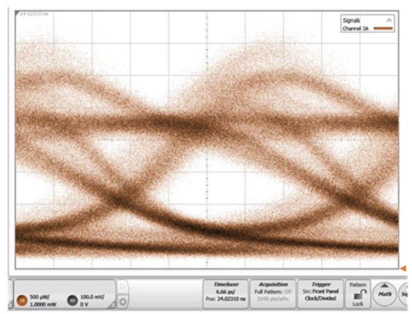
- Optical power-current-voltage (L-I-V) response is temperature-dependent
- Bandwidth is bias and temperature dependent

Measured and Simulated 25Gb/s Eye Diagrams

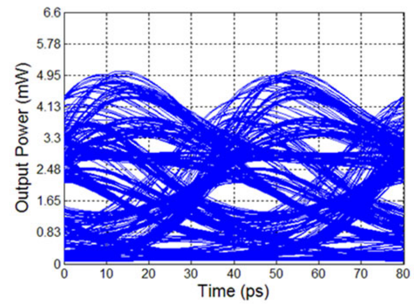
T_s=23°C | T_s=80°C

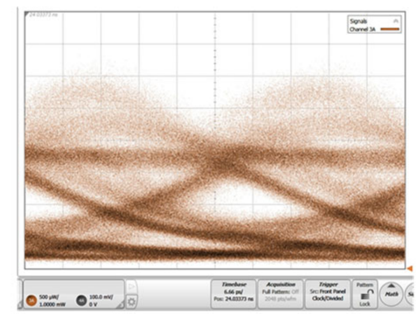
I_b=4mA



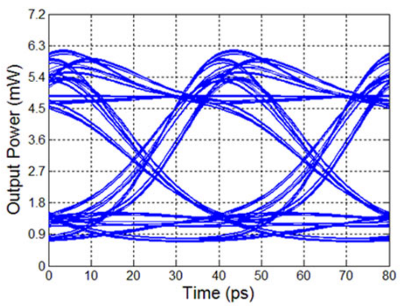


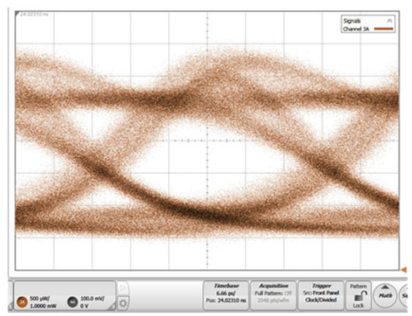
I_b=4mA



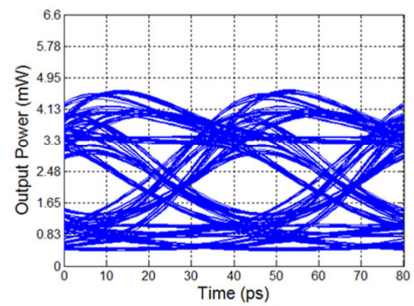


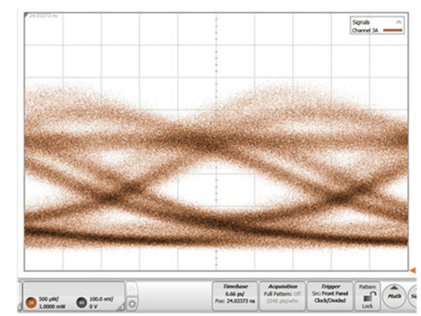
I_b=5mA



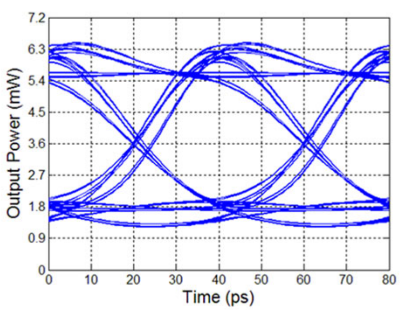


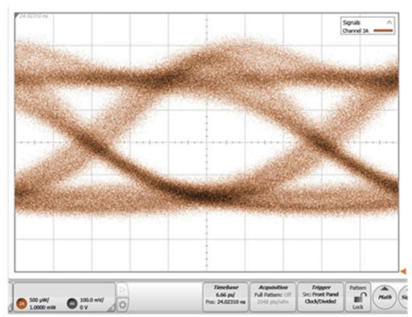
I_b=5mA



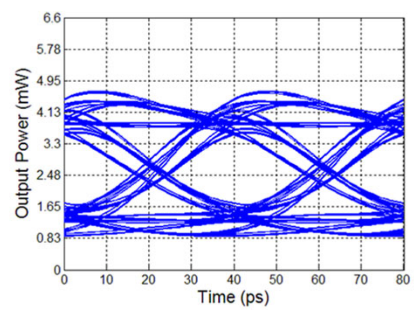


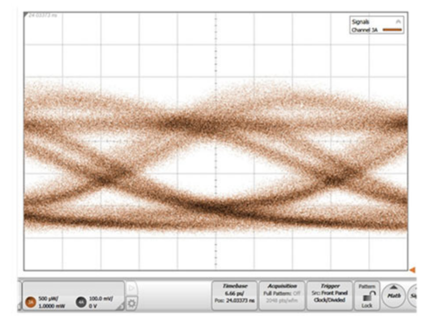
I_b=6mA





I_b=6mA

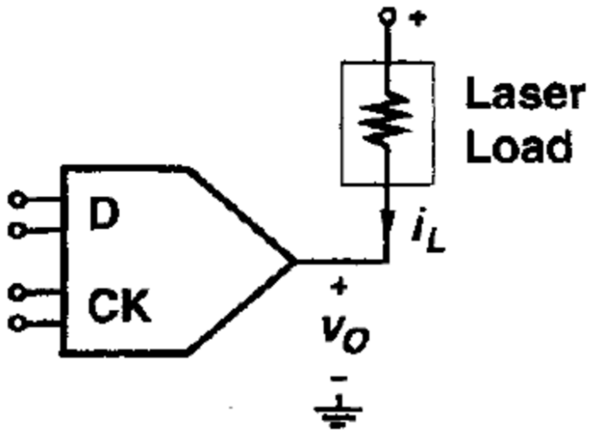


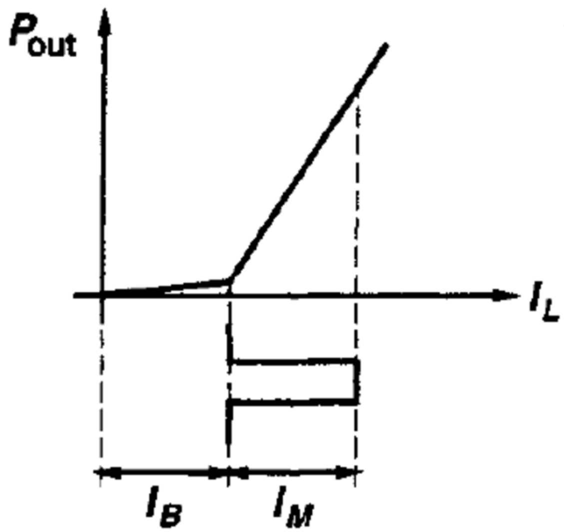


VCSEL Performance Issues

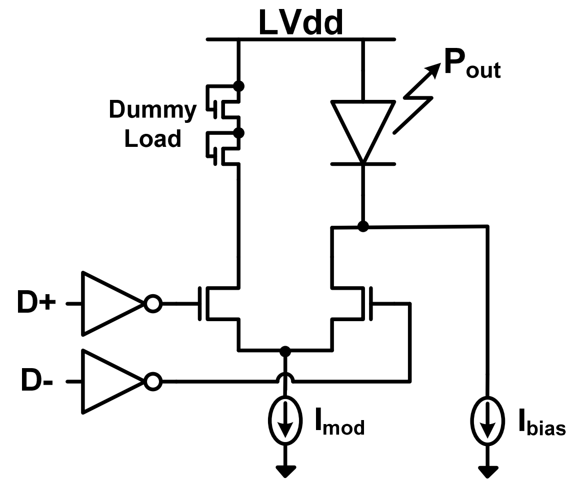
- Threshold Current
  - Reduced with smaller devices, better electron/photon confinement (quantum wells)
- Bias Dependent Frequency Response
  - Proportional to Sqrt(Ibias)
  - Low damping factor causes relaxation oscillations in step response
- Turn-On Delay
  - Leads to data-dependent jitter if biased 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





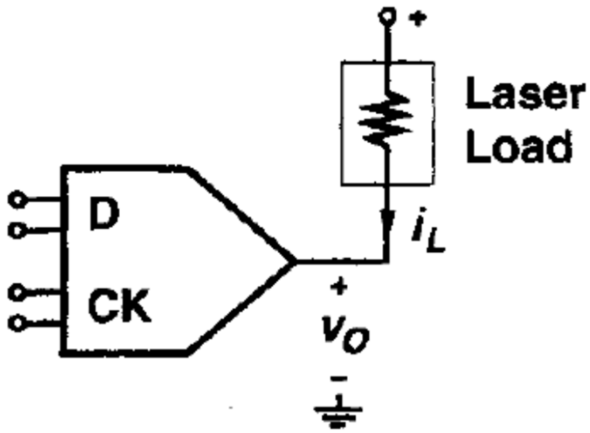
Current-Mode VCSEL Driver

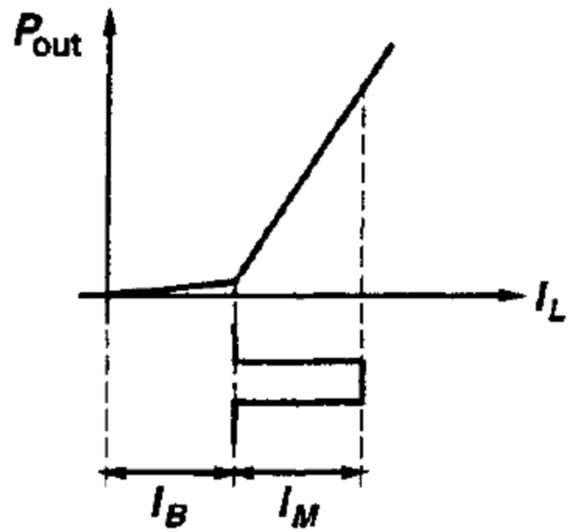


- Current-mode drivers are often used due to the laser's linear L-I relationship

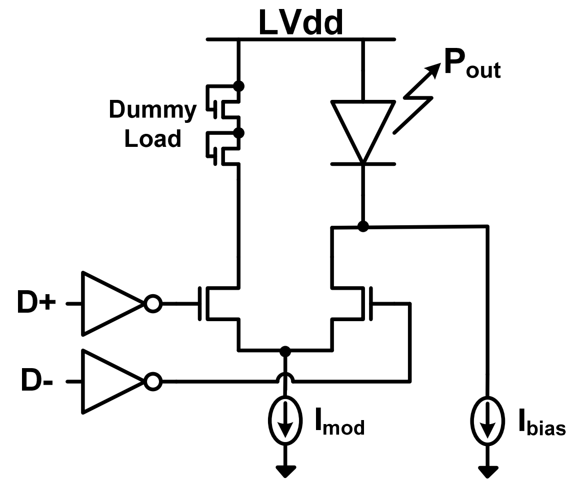
- In addition to the high-speed modulation current I_M, laser drivers must also supply a bias current I_B to ensure a minimum frequency response and/or eliminate turn-on delay

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

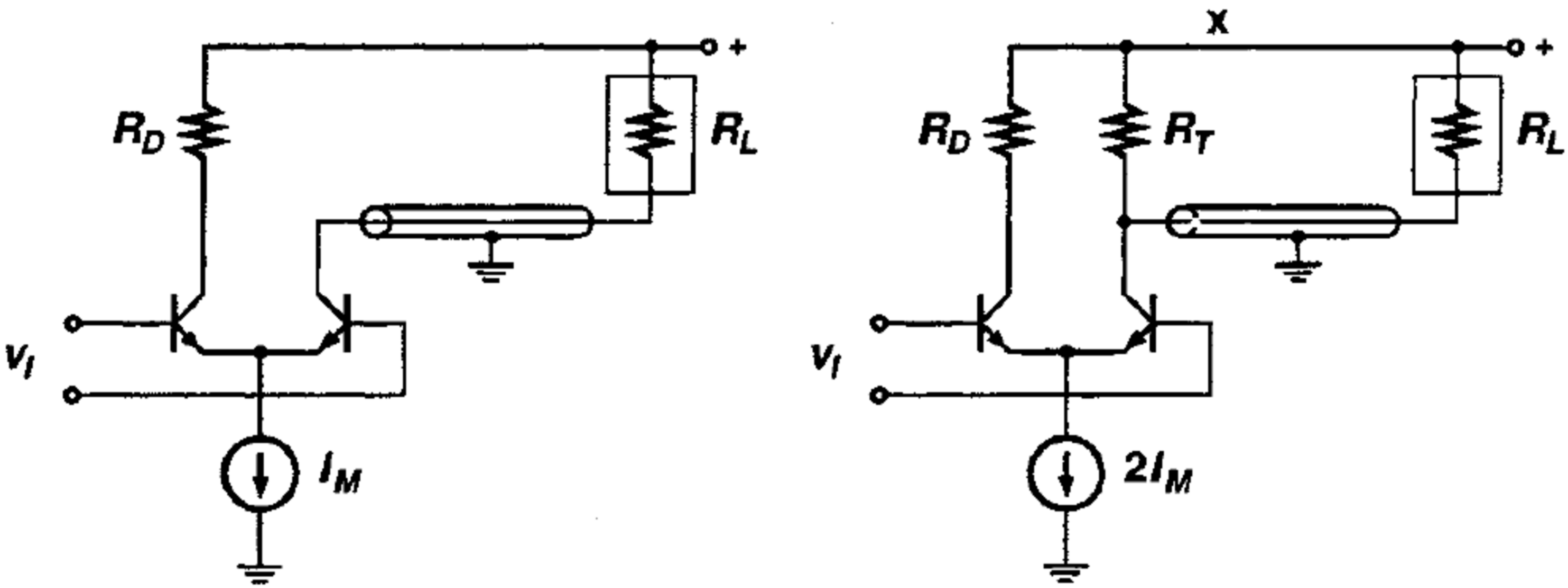
$$I_{L,0} = I_B \qquad I_{L,1} = I_B + I_M$$

- AC-coupled case

The bias current is the average current

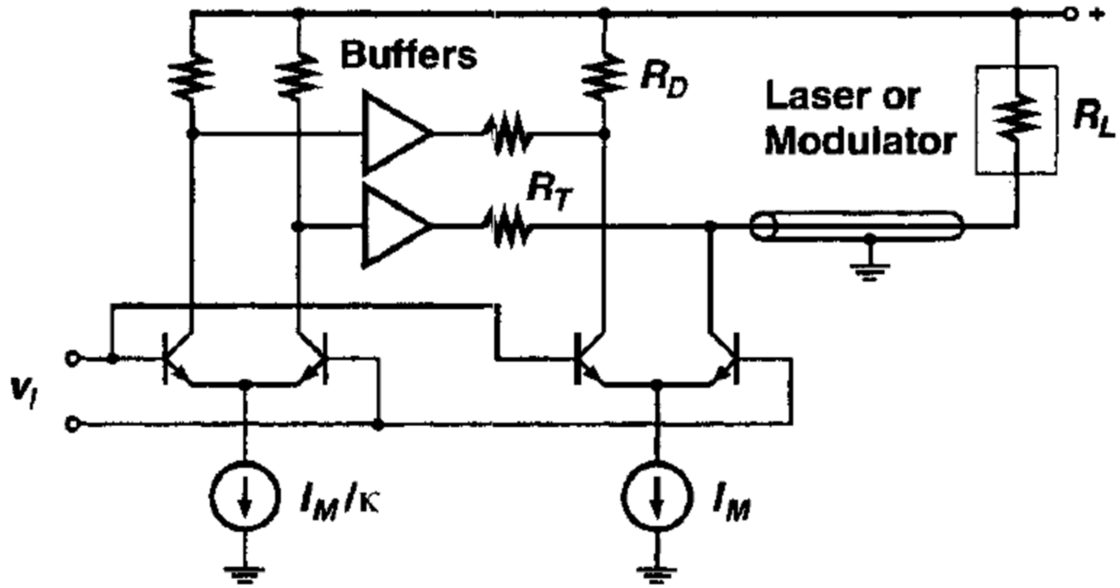
$$I_{L,0} = I_B - \frac{I_M}{2} \qquad I_{L,1} = I_B + \frac{I_M}{2}$$

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

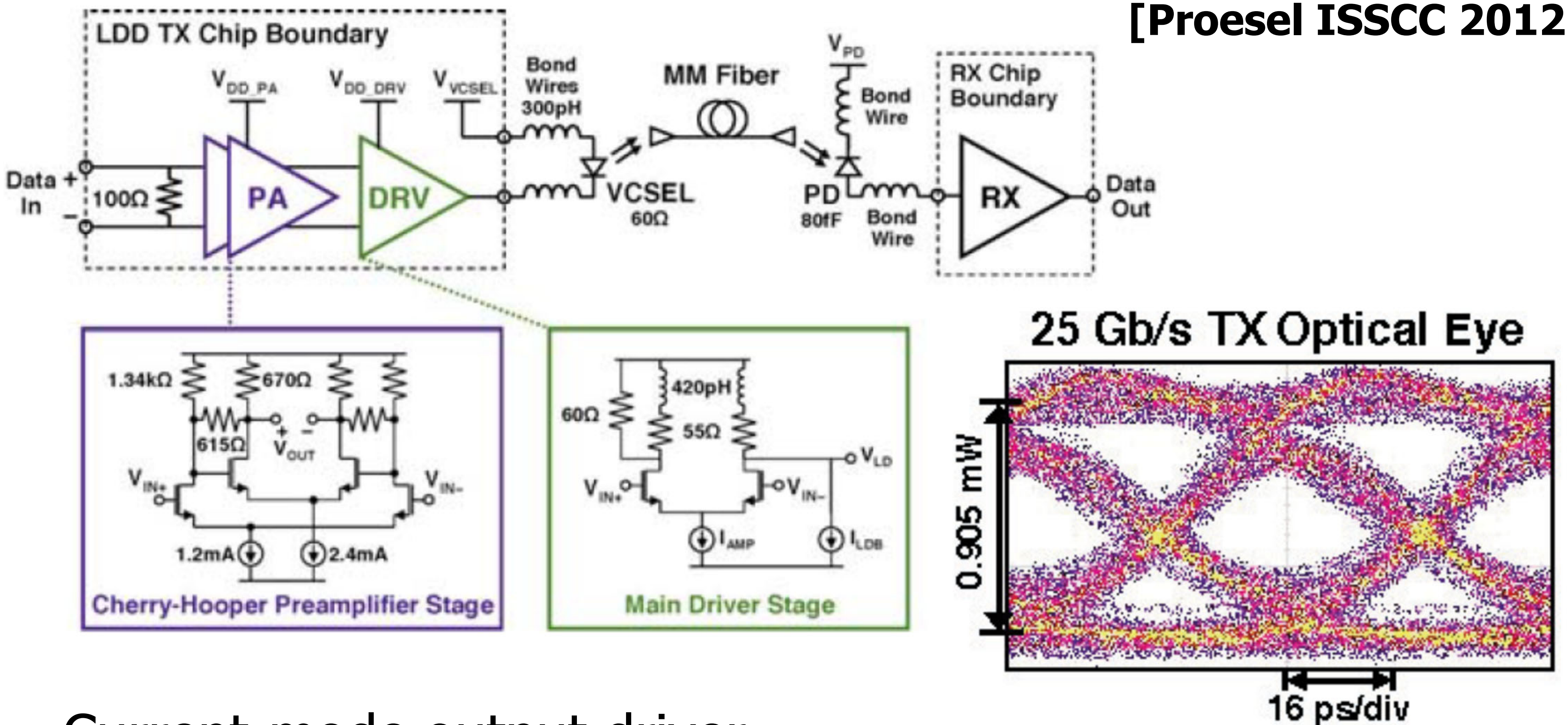
Active Back Termination



- 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

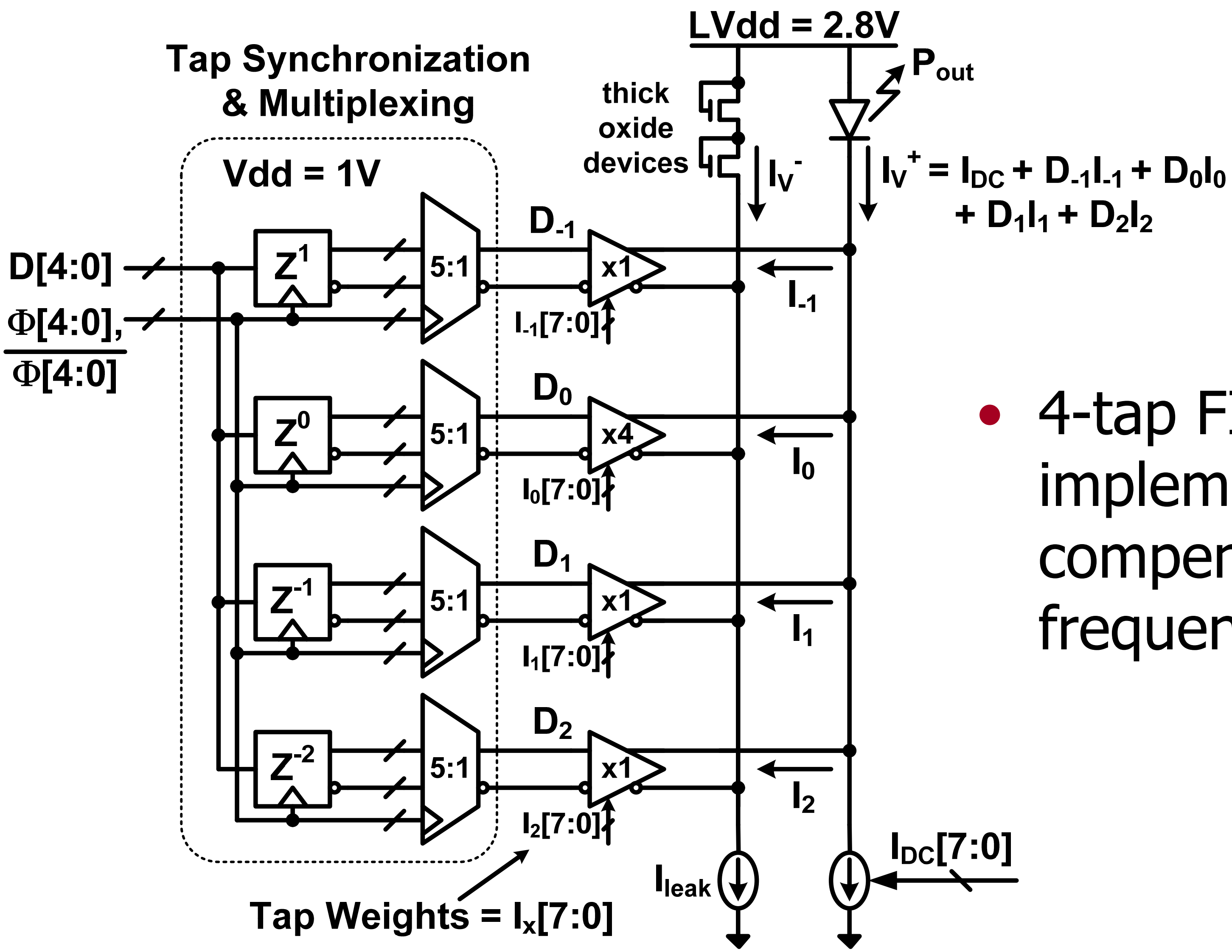
25Gb/s VCSEL Link

[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

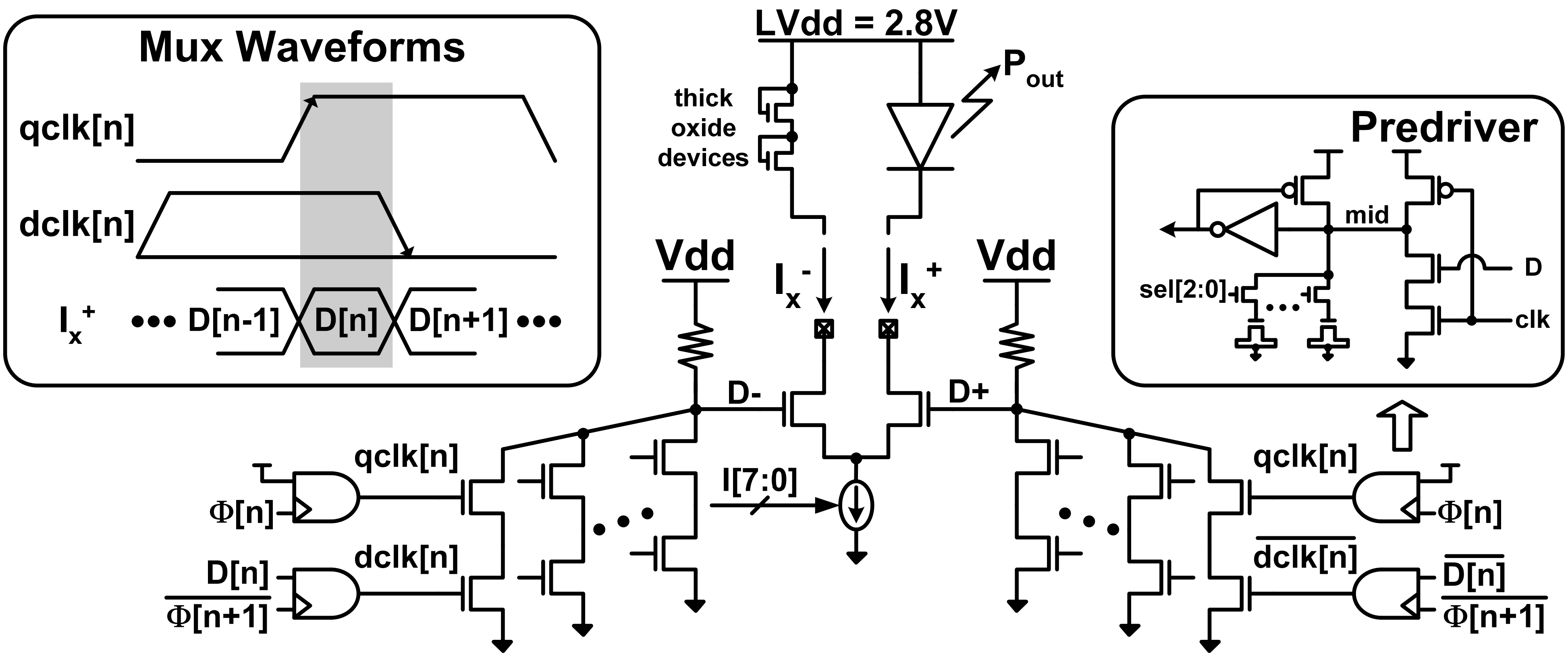
Multiplexing FIR Output Driver



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

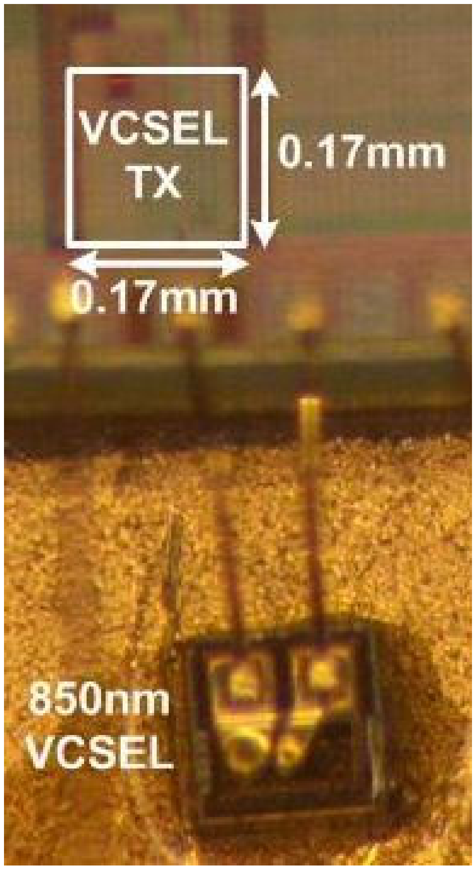
S. Palermo and M. Horowitz, "High-Speed Transmitters in 90nm CMOS for High-Density Optical Interconnects," *ESSCIRC*, 2006.

Tap Mux & Output Stage

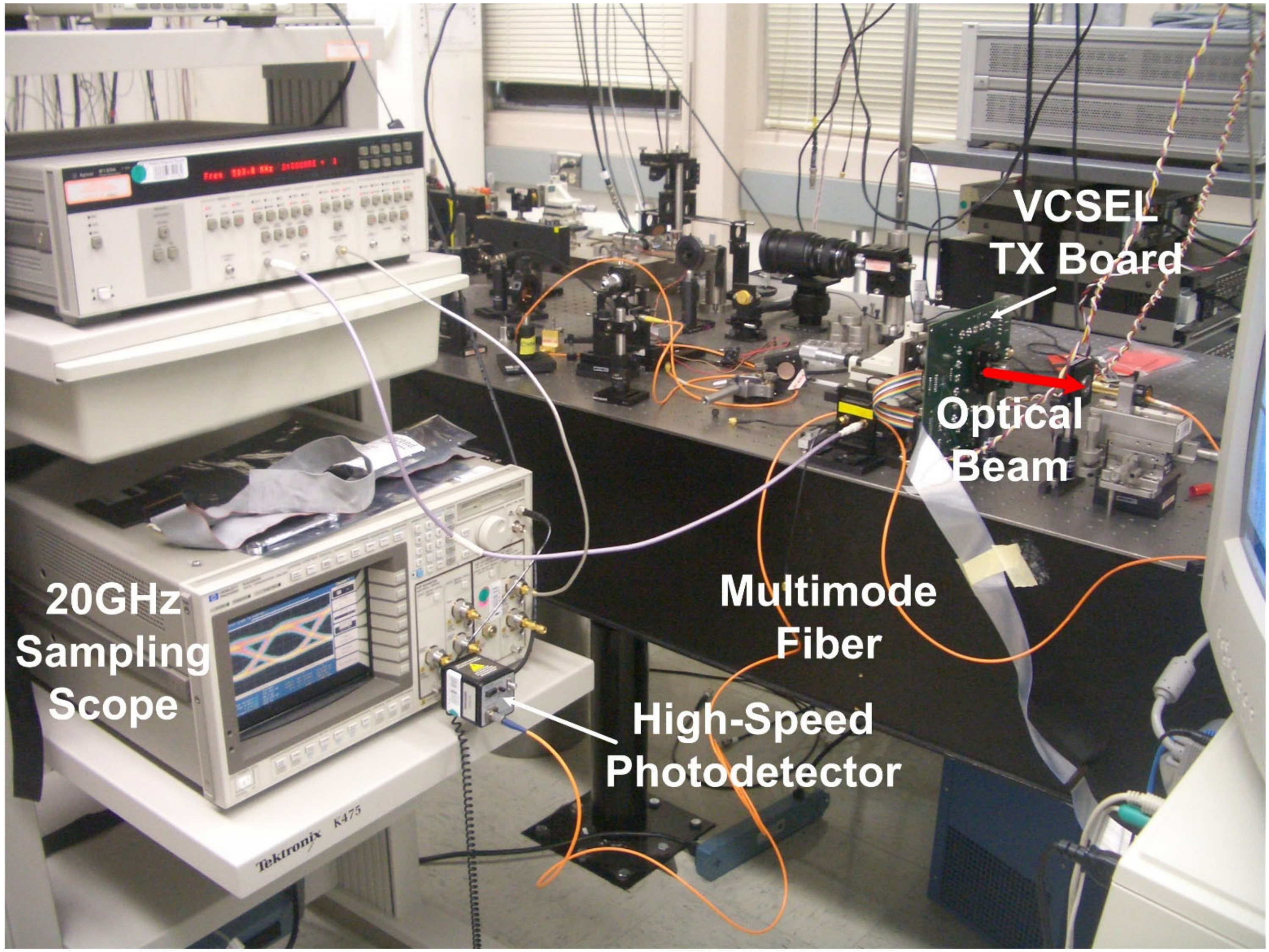


- 5:1 multiplexing predriver uses 5 pairs of complementary clock phases spaced by a bit time
- Tunable delay predriver compensates for static phase offsets and duty cycle error

VCSEL TX Optical Testing



Wirebonded
10Gb/s VCSEL



VCSEL 16Gb/s Optical Eye Diagrams

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

No Equalization

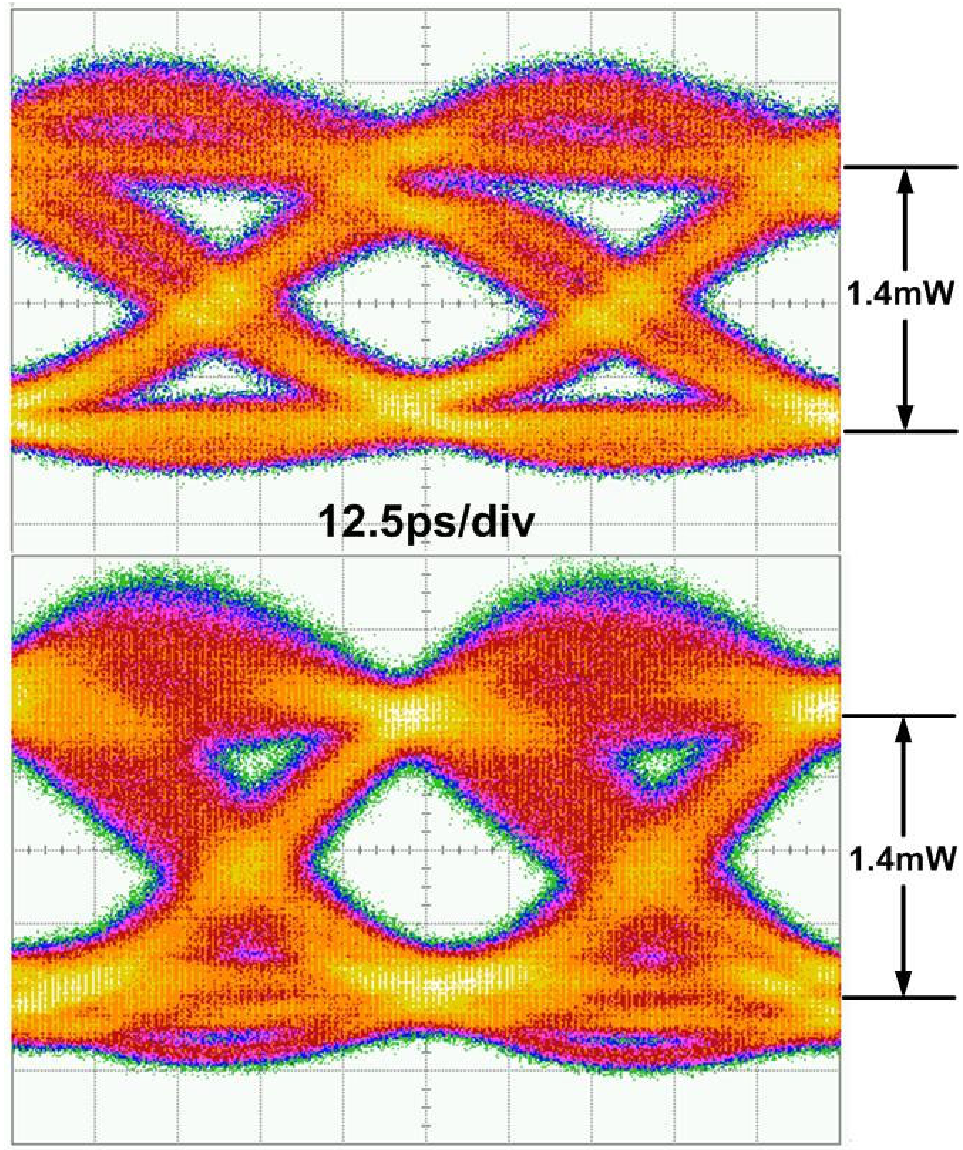
I_{DC} = 4.37mA
I_{MOD} = 3.66mA

w/ Equalization

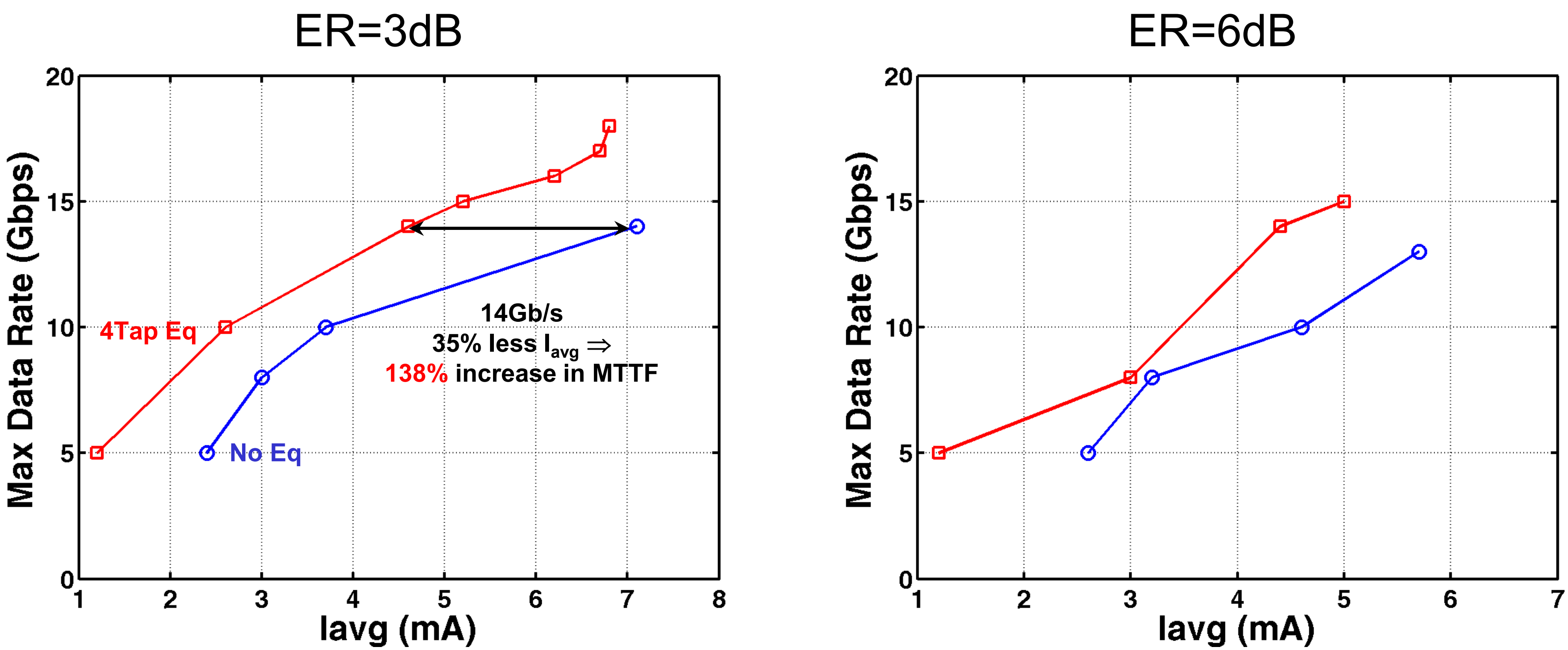
I_{DC} = 3.48mA
I_{-1} = -0.70mA
I_0 = 4.36mA
I_1 = -0.19mA
I_2 = 0.19mA

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

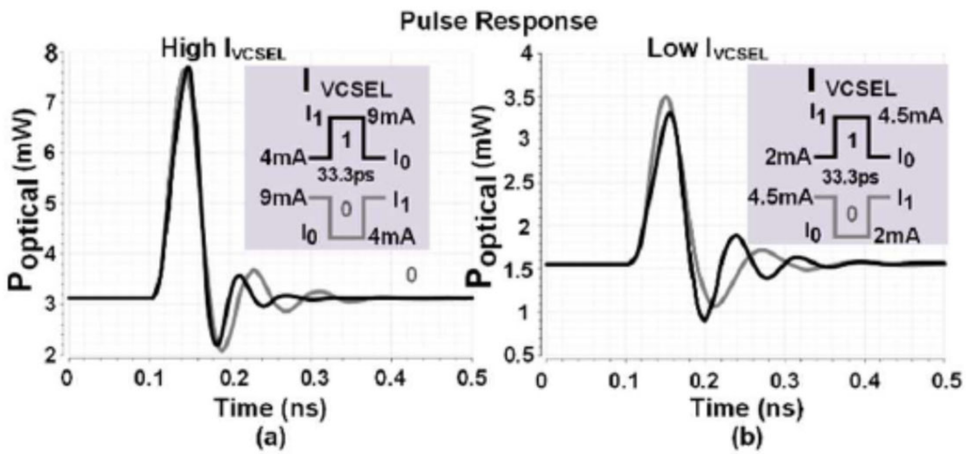
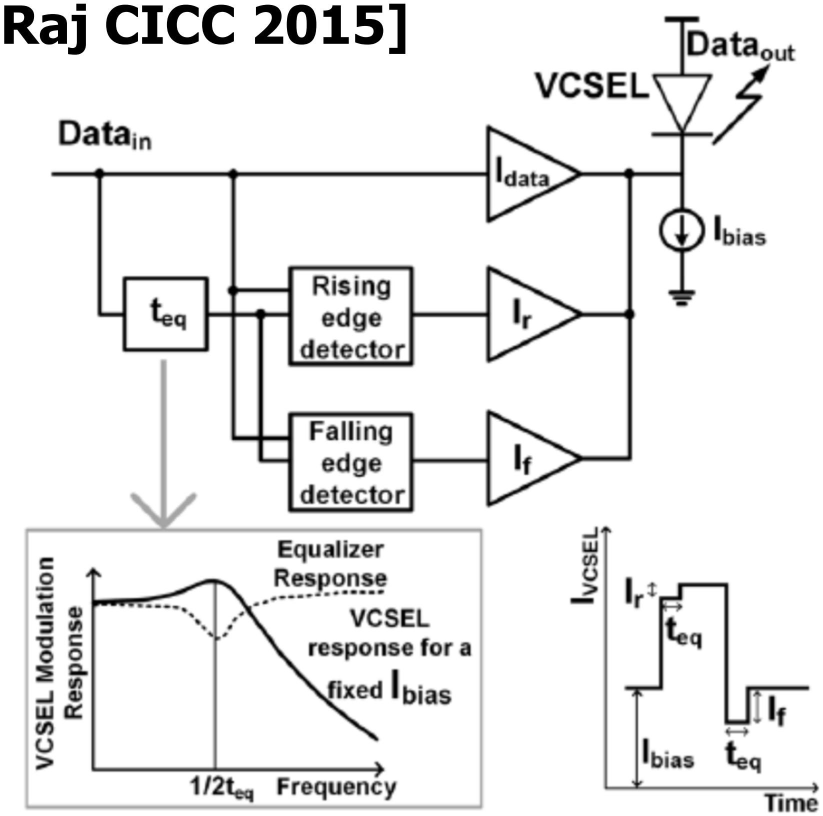


Fig. 2. VCSEL pulse responses for (a) high and (b) low I_{VCSEL}.

[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

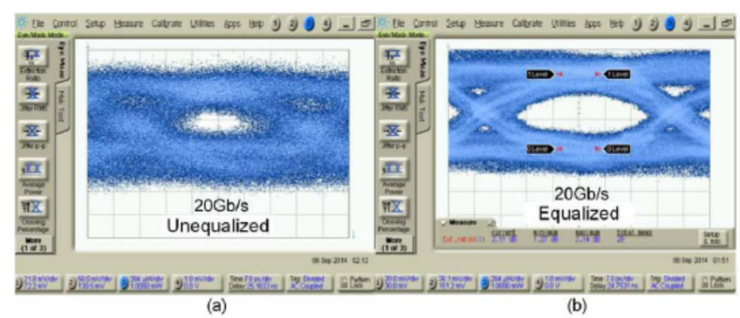
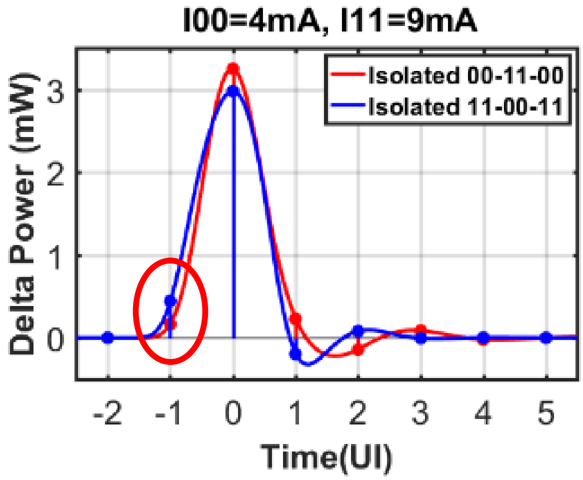
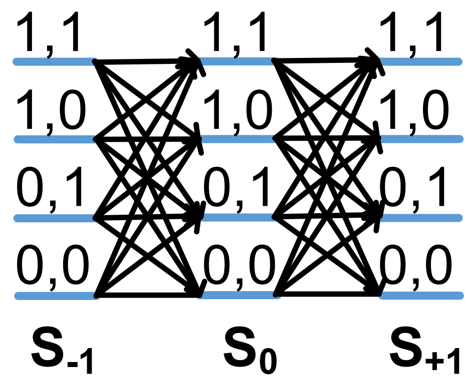


Fig. 8 Measured optical eye-diagram for PRBS-15 data at 20Gb/s. (a) Unequalized (b) Equalized.

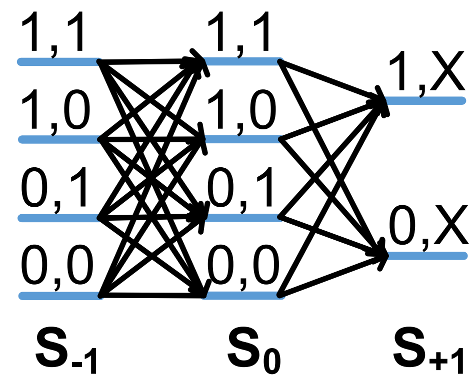
PAM4 VCSEL Driver w/ 2.5-Tap Nonlinear FFE

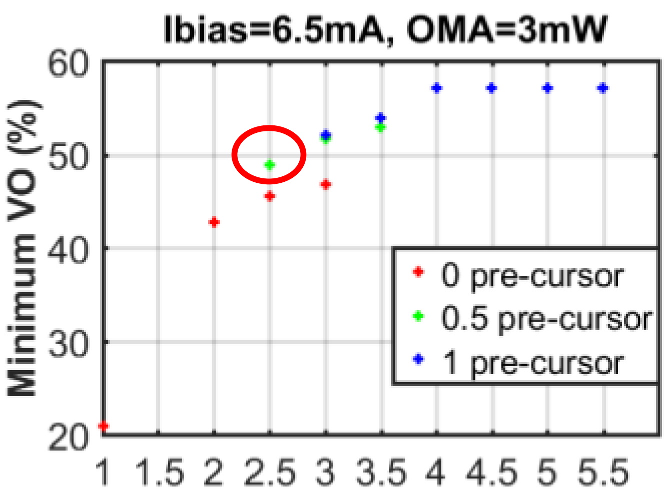


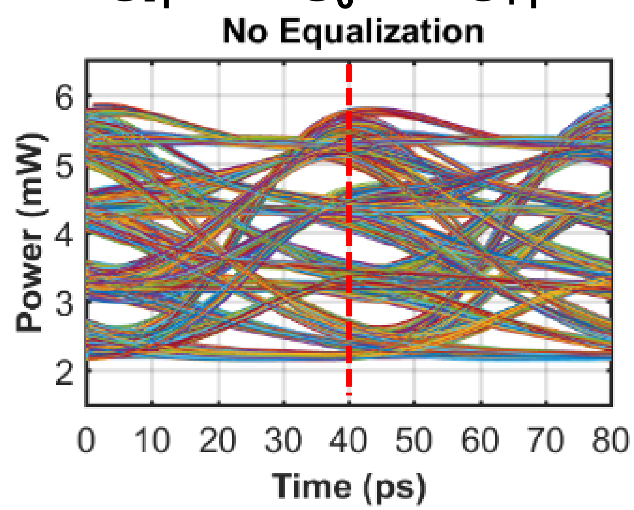
3-tap equalizer

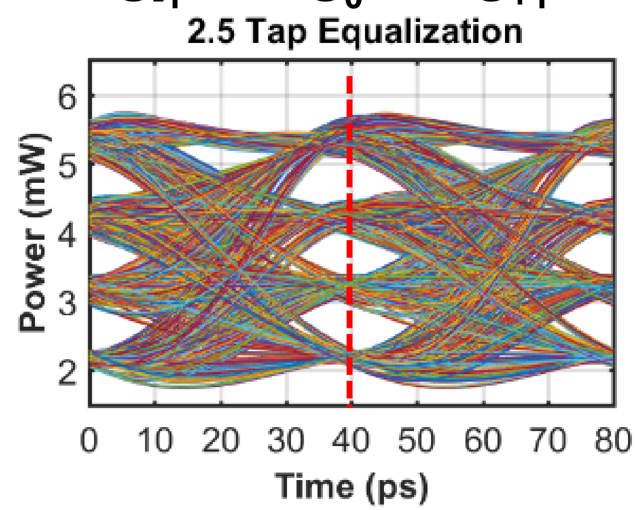


2.5-tap equalizer with the pre-cursor weight only a function of the MSB





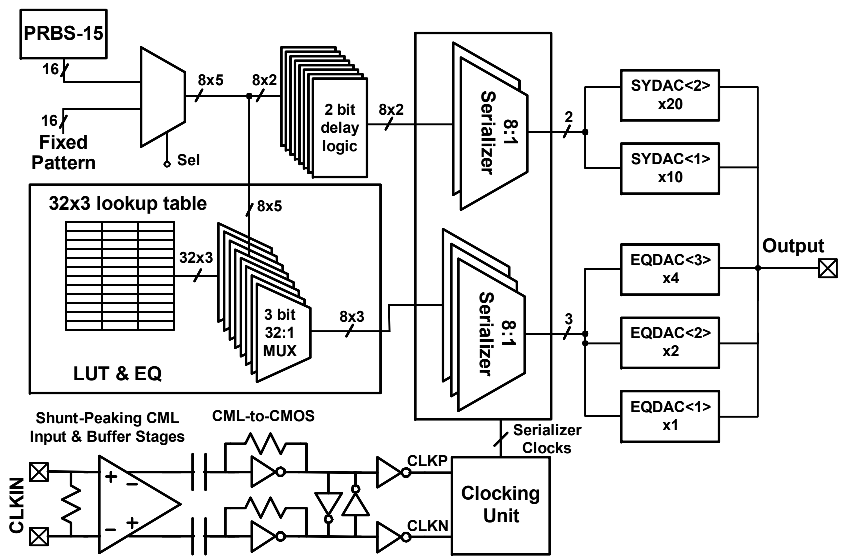




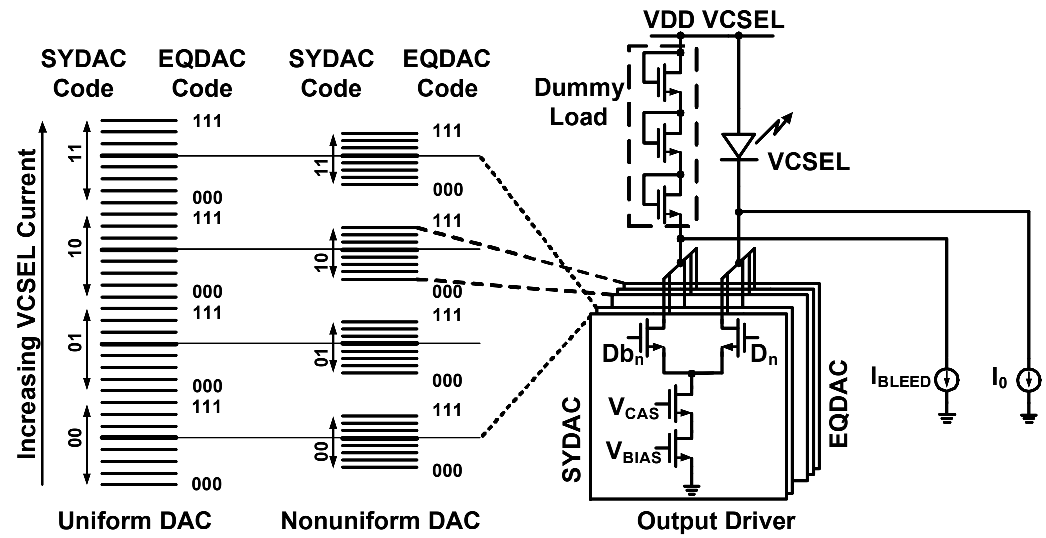
- A 2.5-tap nonlinear equalizer, with the first pre-cursor weight only dependent on the MSB, is a good compromise between complexity and performance

Serializing VCSEL TX & Output Stage

Serializing VCSEL TX



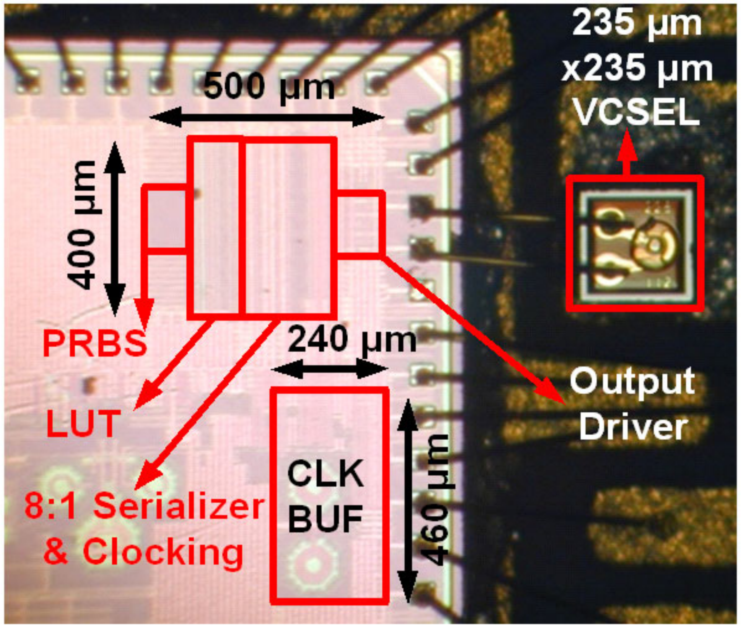
5-b Non-Uniform Current DAC Driver



- 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

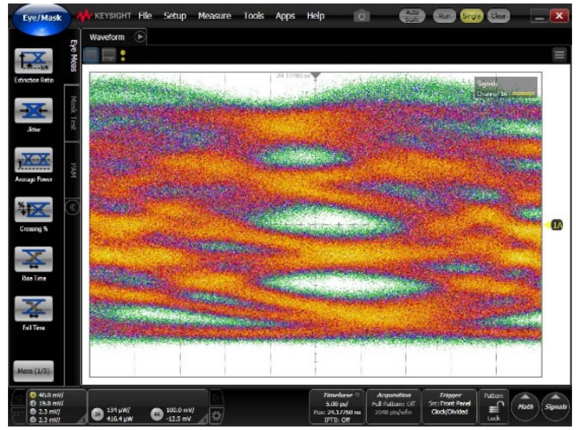
50Gb/s PAM4 Experimental Results

[Tyagi PTL 2018]

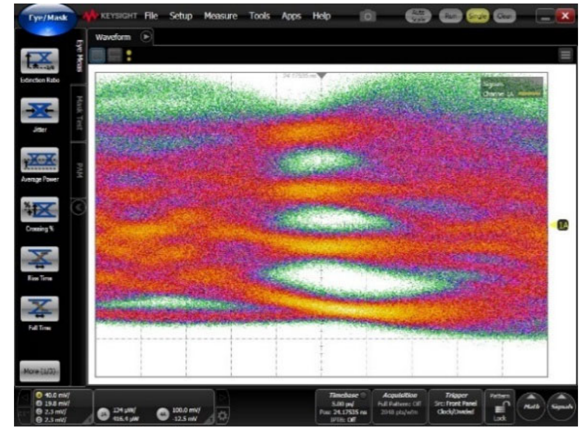


- Core transmitter area is $0.2mm^2$

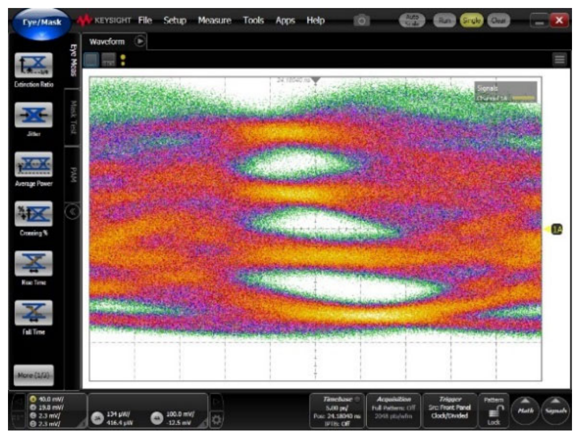
No Equalization



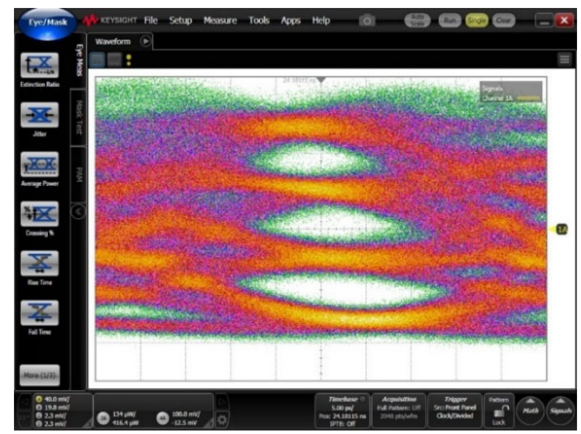
2-Tap Linear



2.5-Tap Linear



2.5-Tap Nonlinear



- 2.5 tap nonlinear equalizer improves eye height and timing alignment of the 3 PAM4 eyes

Next Time

- Mach-Zehnder Modulator (MZM) TX