ECEN721: Optical Interconnects Circuits and Systems Spring 2024

Lecture 10: Electroabsorption Modulator Transmitters

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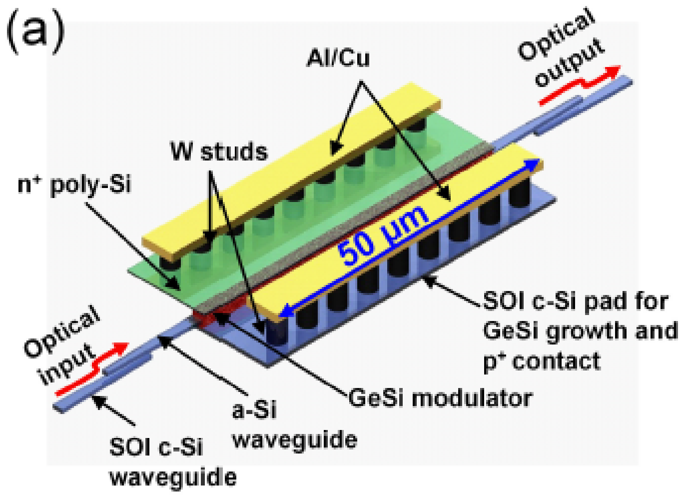
Announcements

- Reading
  - Sackinger Chapter 8

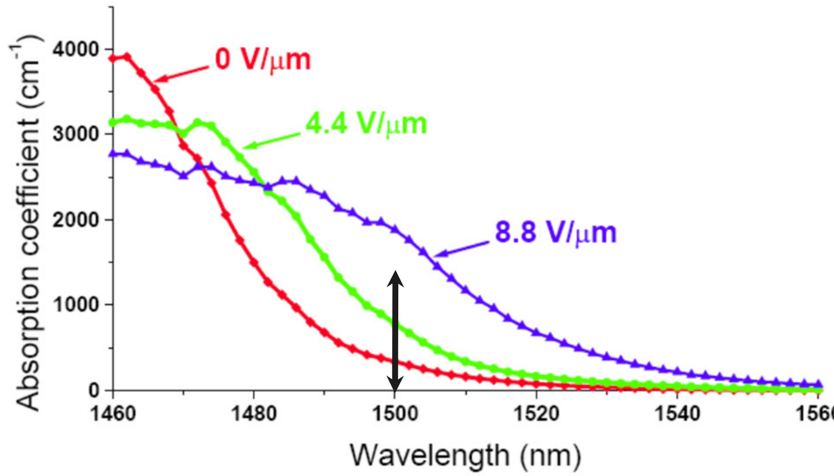
Agenda

- EAM device operation and modeling
- EAM drivers
  - Controlled-impedance drivers
  - Lumped-element drivers

Electroabsorption Modulator (EAM)



Waveguide EAM [Liu 2008]

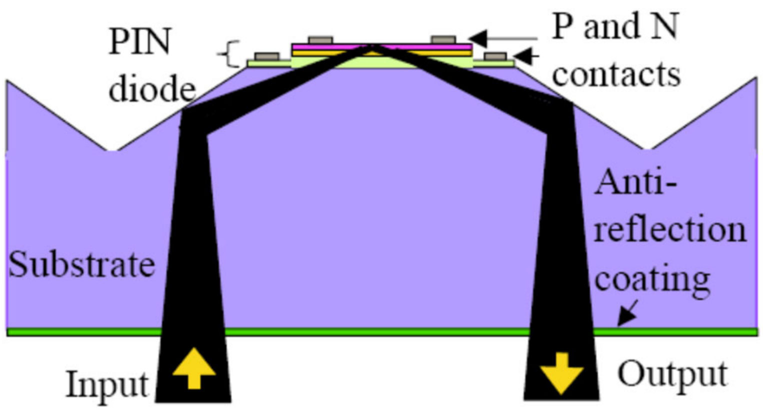


[Helman JSTQE 2005]

- Electroabsorption modulators operate with voltage-dependent absorption of light passing through the device
- The device structure is a reverse-biased p-i-n diode
- The Franz-Keldysh effect describes how the effective bandgap of the semiconductor decreases with increasing electric field, shifting the absorption edge
- While this effect is weak, it can be enhanced with device structures with multiple quantum wells (MQW) through the quantum-confined Stark effect

EAM Device Types

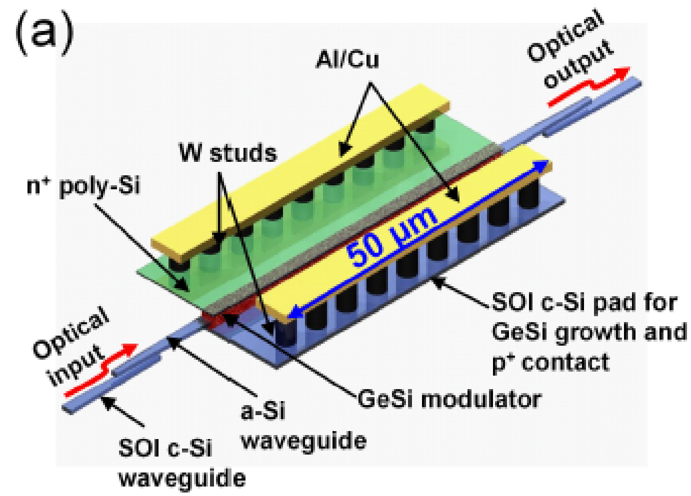
Surface Normal EAM*



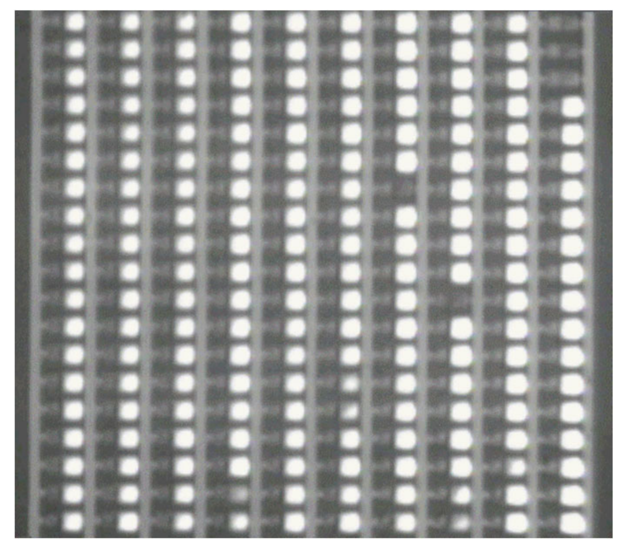
[Helman JSTQE 2005]

- EAMs can be waveguide-based or surface normal
- Waveguide-based structures typically allow for higher extinction ratios due to the increased absorption length
- Surface normal devices provide the potential for large arrays of optical I/Os through bonding

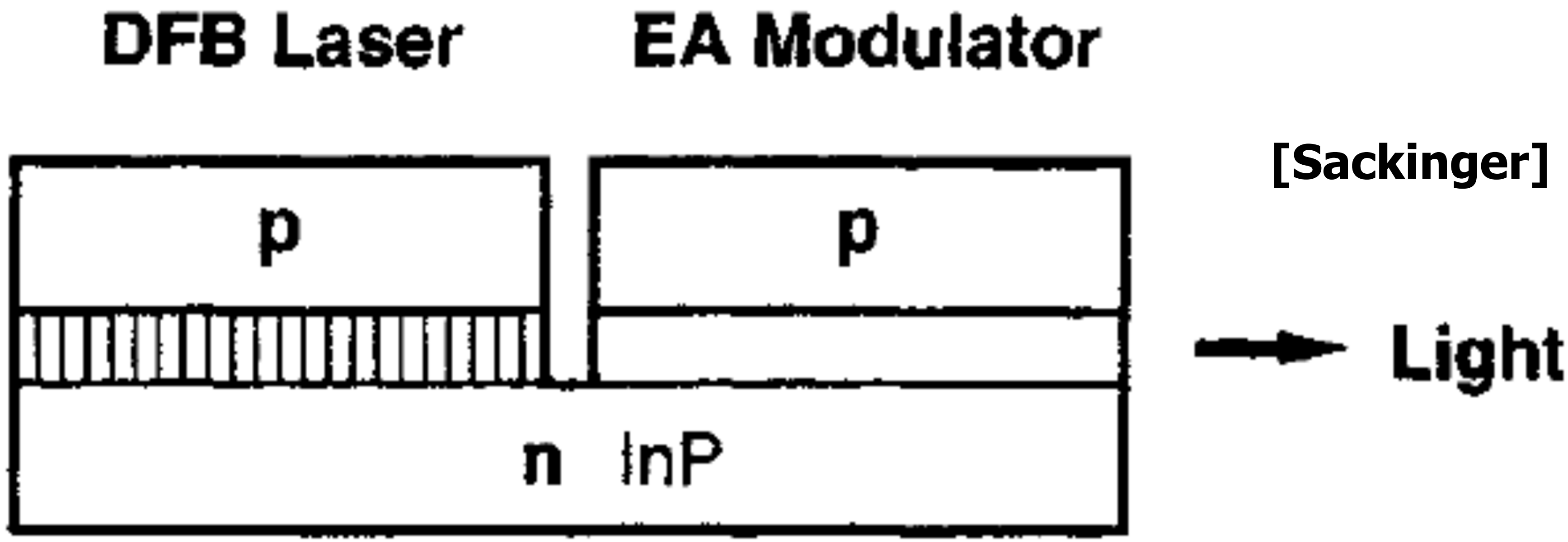
Waveguide EAM [Liu 2008]



MQW EAM Array Bonded onto a CMOS Chip [Keeler 2002]



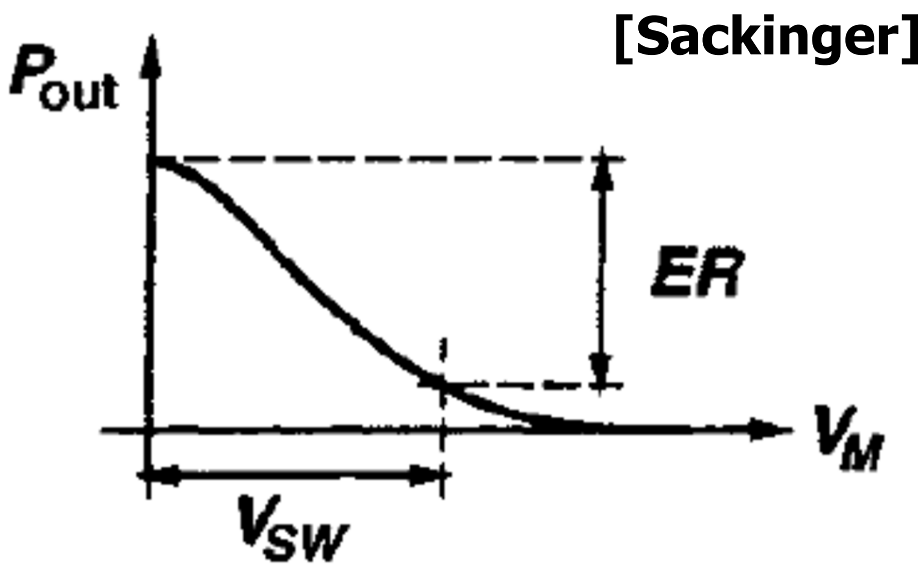
Electroabsorption Modulated Laser (EML)



[Sackinger]

- In direct-bandgap III-V technologies, an EAM can be monolithically integrated with a laser to form an Electroabsorption Modulated Laser (EML)
- This is a very compact device structure which has low coupling losses

EAM Switching Curve

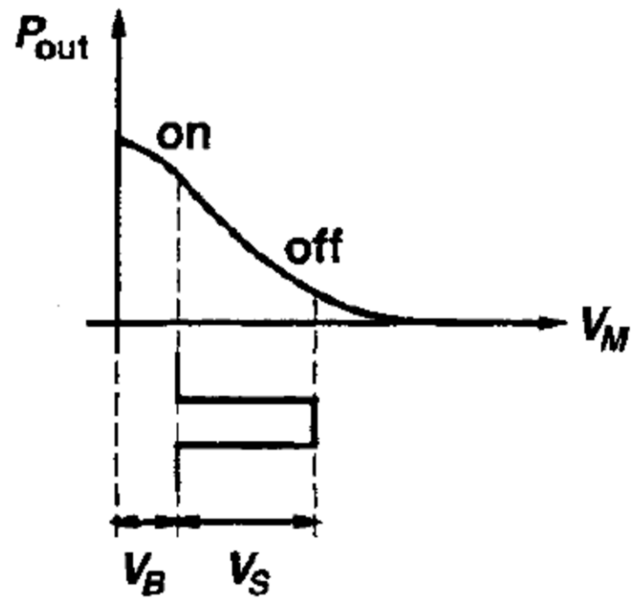


- At low reverse-bias, the device ideally has low absorption and most of the light appears at the output
- The absorption increases when a strong reverse-bias is applied and less power appears at the output
- EAMs are characterized with a switching voltage V_{SW} that corresponds to a given extinction ratio
- Typical switching voltages are 1.5 to 4V

EAM Chirp

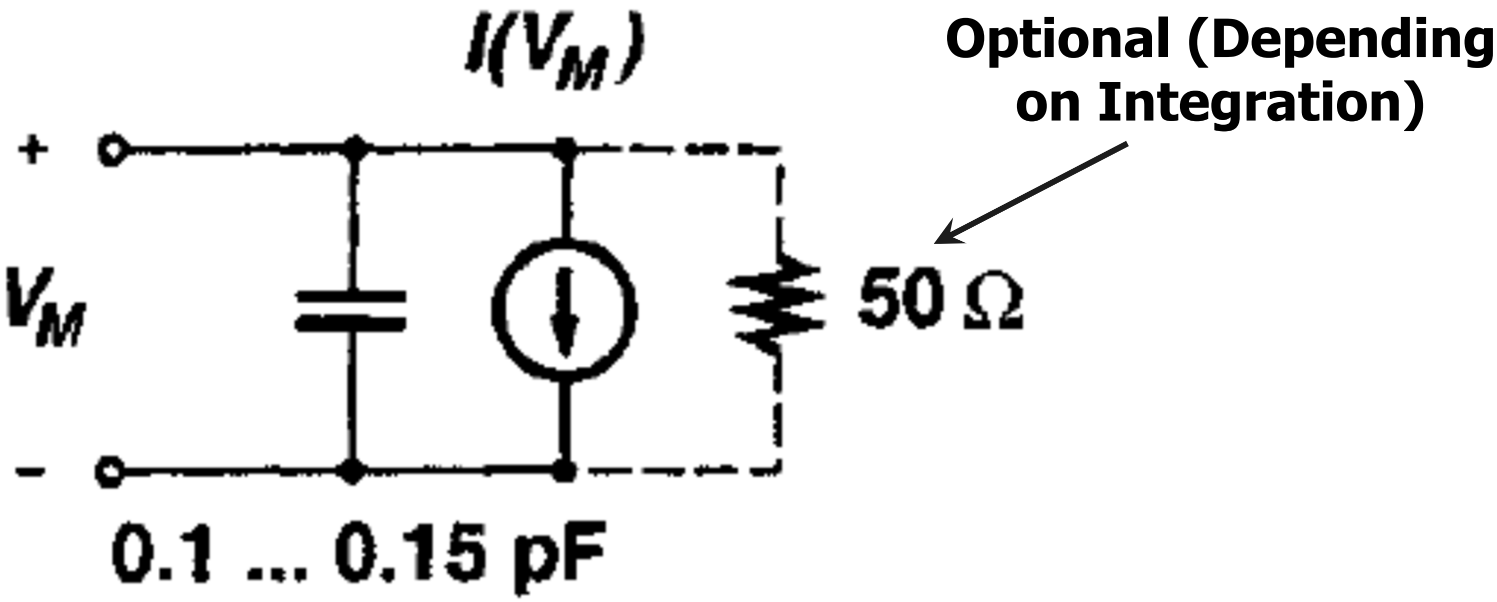
- The modulation voltage not only changes the absorption, but also the refractive index, inducing some chirp in the EAM output
- This chip is generally much less than a directly-modulated laser, with $|\alpha|<1$
- Application of a small on-state bias (0-1V) can minimize this chirp at the cost of higher insertion loss

EAM Bias & Modulation Voltages



- The voltage swing V_S is set to achieve a sufficient extinction ratio, i.e. higher than V_{SW}
  - Typical Range: 0.2-3V
- The bias voltage V_B is set to minimize the chirp at the cost of higher insertion loss
  - Typical Range: 0-1V

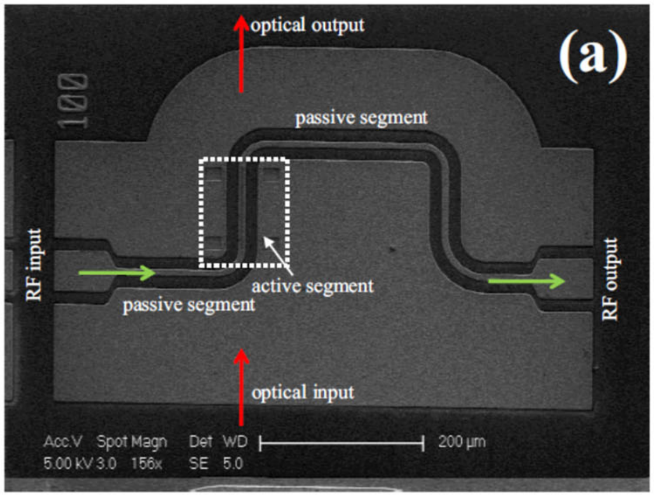
EAM Electrical Model

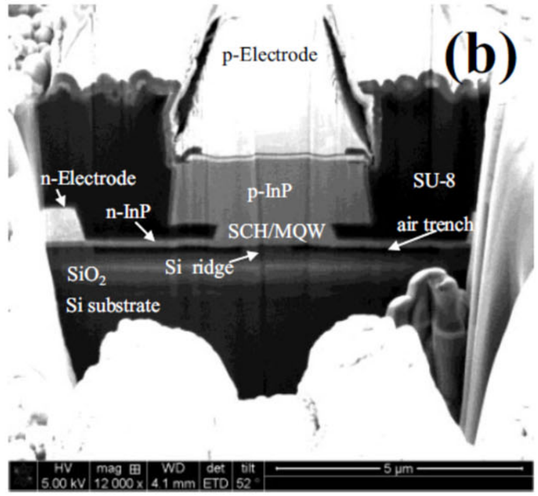


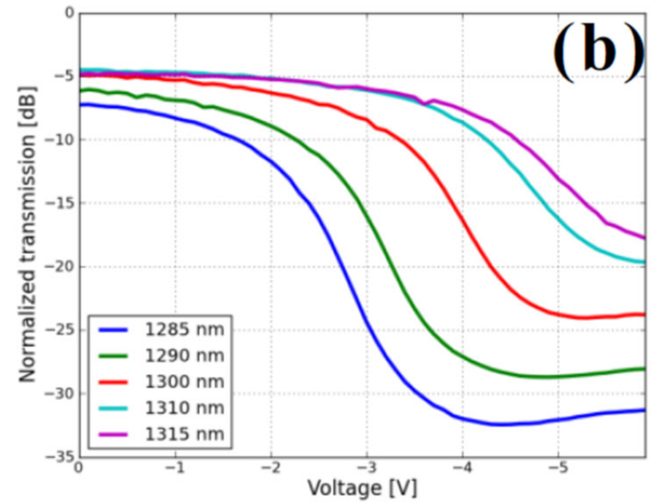
- Electrically, the EAM is a reverse-based diode
- This is modeled with the diode capacitance and a voltage-dependent photocurrent source (nonlinear resistance)
- Depending on the integration level with the driver, the device may also include a termination resistor

67GHz Hybrid Silicon (InP) EAM

[Tang OFC 2012]

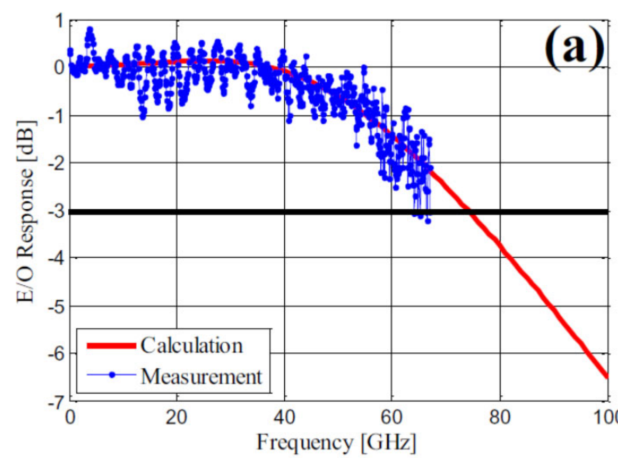


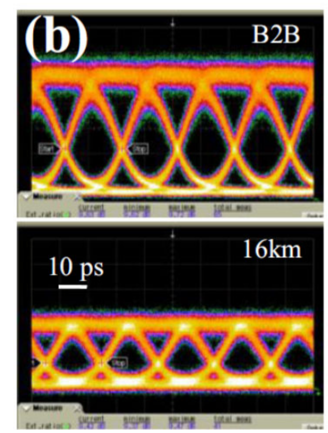




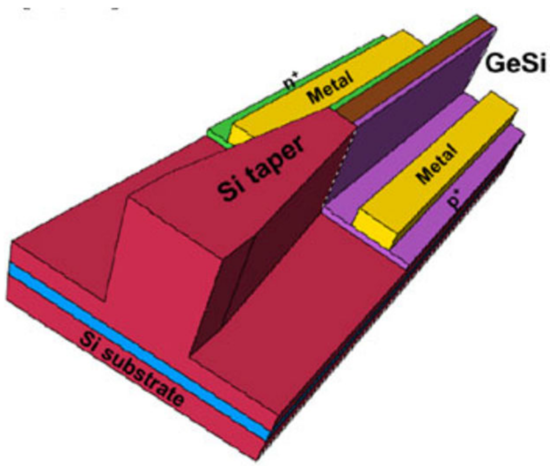
- EAM is formed with an InP p-i-n diode bonded onto silicon
- Design for a controlled-impedance driver
- Nominal 1300nm operation with -4V bias and 2V drive achieves ~15dB ER

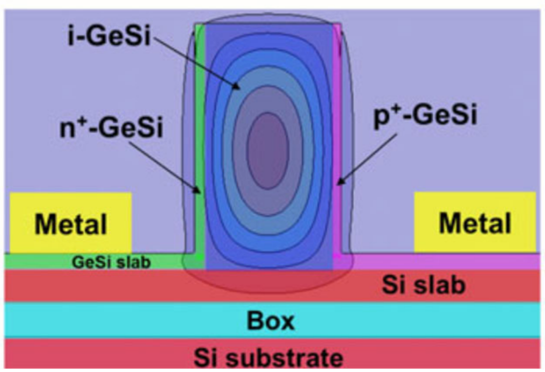
50Gb/s

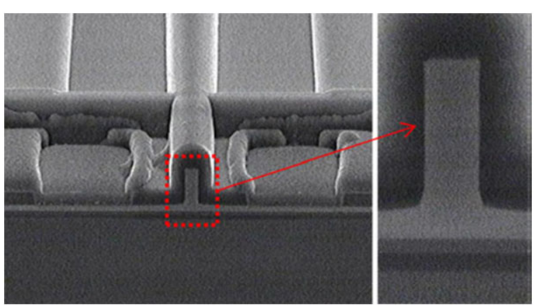




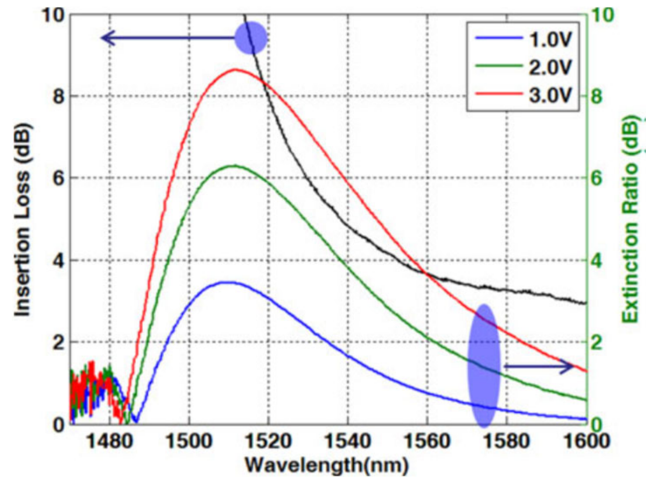
28Gb/s GeSi EAM on SOI



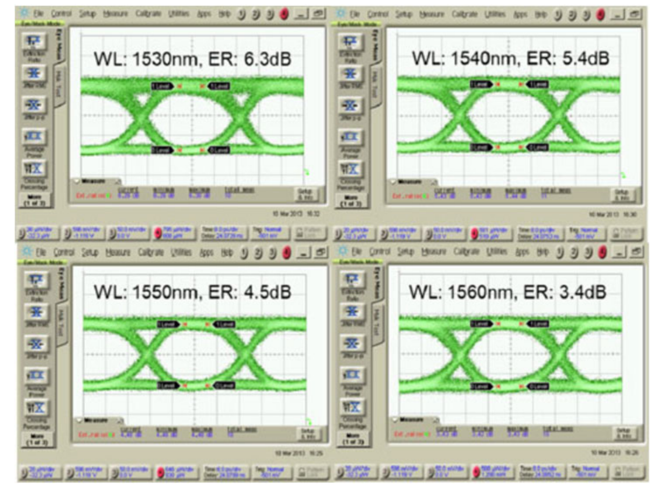




[Feng JSTQE 2013]



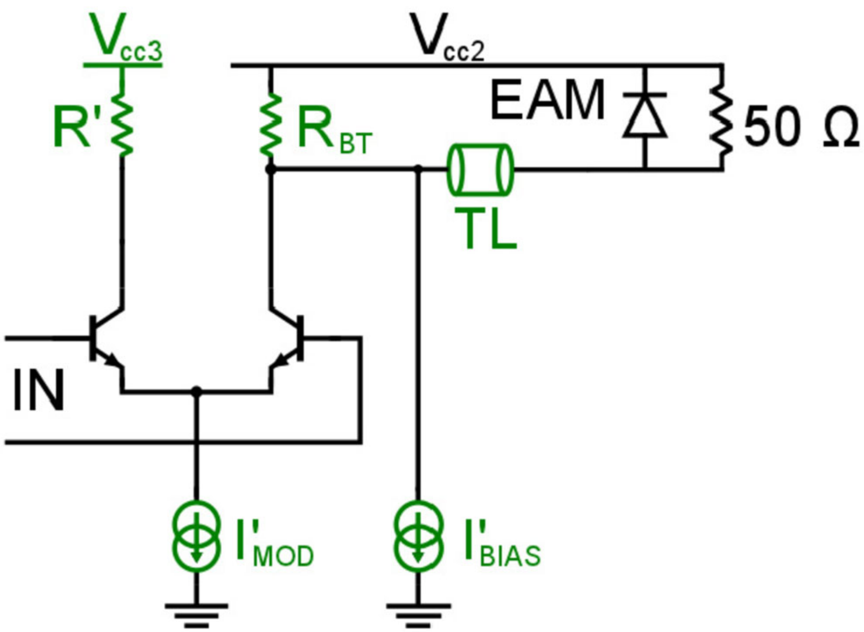
28Gb/s w/ 3V Swing



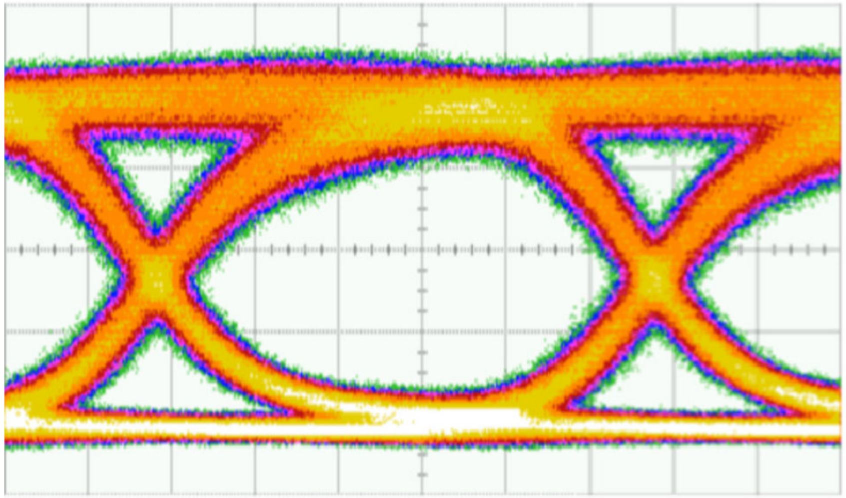
- EAM is formed with an GeSi p-i-n diode fabricated in an SOI platform
- Device is only 50um long and can be driven with a lumped-element driver
- Nominal operation with 3V drive achieves 3-6dB ER over a wide wavelength range

Controlled-Impedance EAM Driver

[Vaernewyck Opt. Exp. 2013]



10Gb/s w/ 2.5V swing & -1.7V bias



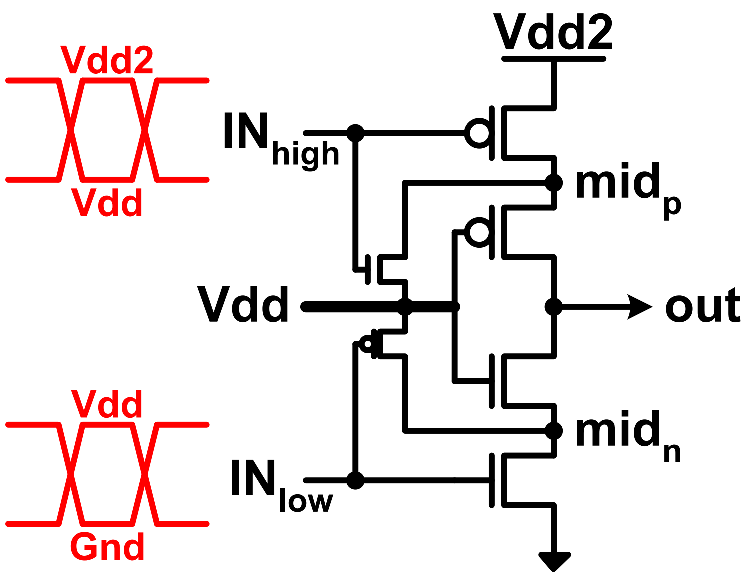
- If the EAM is not tightly integrated with the driver circuitry, then a controlled-impedance driver is required
- The high EAM swings results in large power consumption

CMOS Reliability Constraints

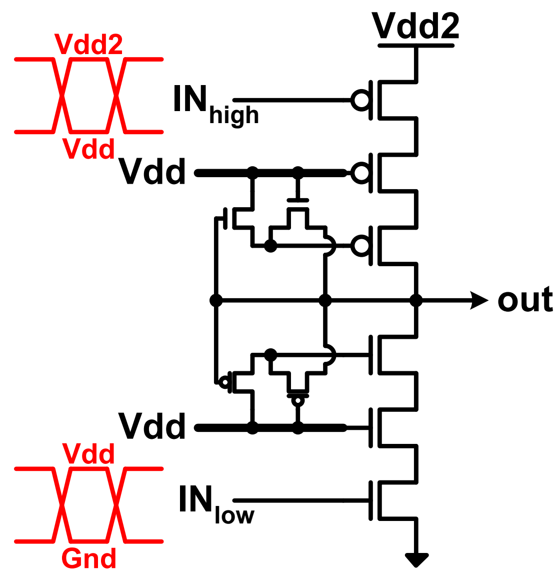
- High electric fields in modern CMOS devices cause many reliability issues
  - Oxide Breakdown
  - Hot-Carrier Degradation
- Higher voltage I/O transistors are too slow
- Core transistor output stage V_{GS}, V_{GD}, V_{DS}
  - Should not exceed 20-30% of nominal Vdd during transients
  - Not greater than Vdd in steady state

High-Voltage Output Stages

Cascode [1]



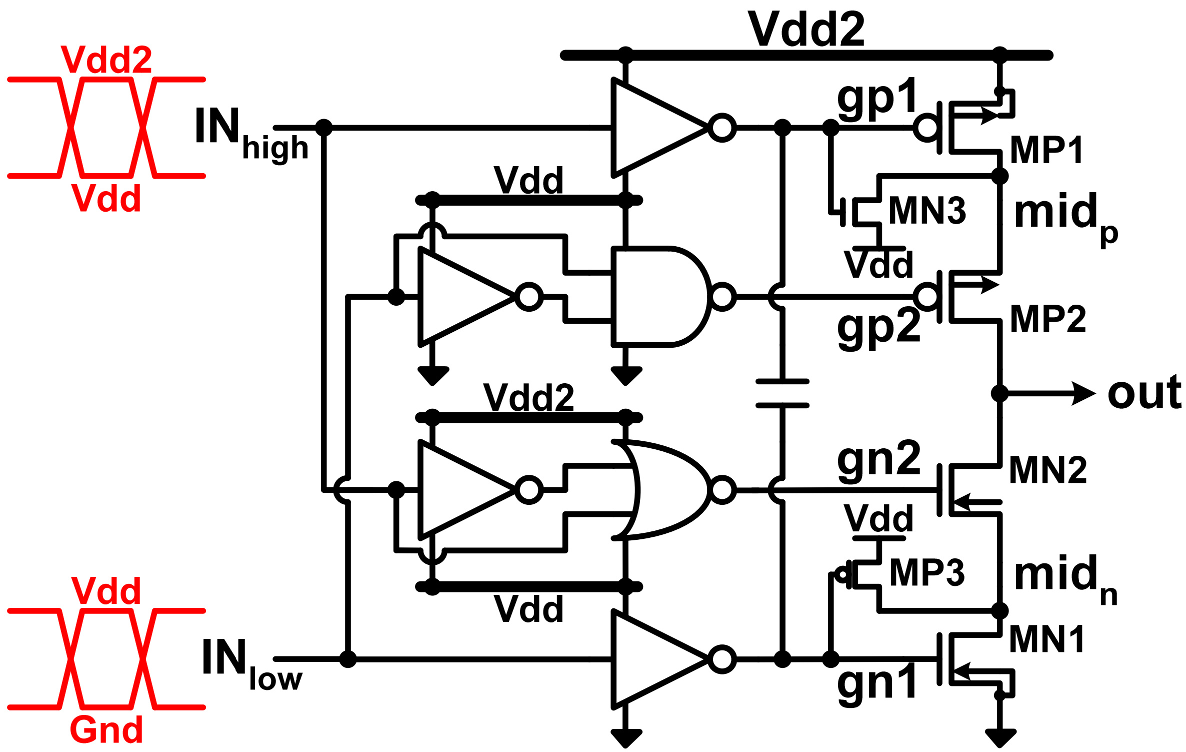
Double Cascode w/ Output Tracking [2]



- Static-biased cascode suffers from V_{DS} stress during transients
- Double-cascode with output tracking is slow due to three transistor stack and feedback loop

1. T. Woodward *et al*, "Modulator-Driver Circuits for Optoelectronic VLSI," *IEEE Photonics Technology Letters*, June 1997.
2. A. Annema *et al*, "5.5-V I/O in a 2.5-V 0.25-μm CMOS Technology," *IEEE Journal of Solid-State Circuits*, Mar. 2001.

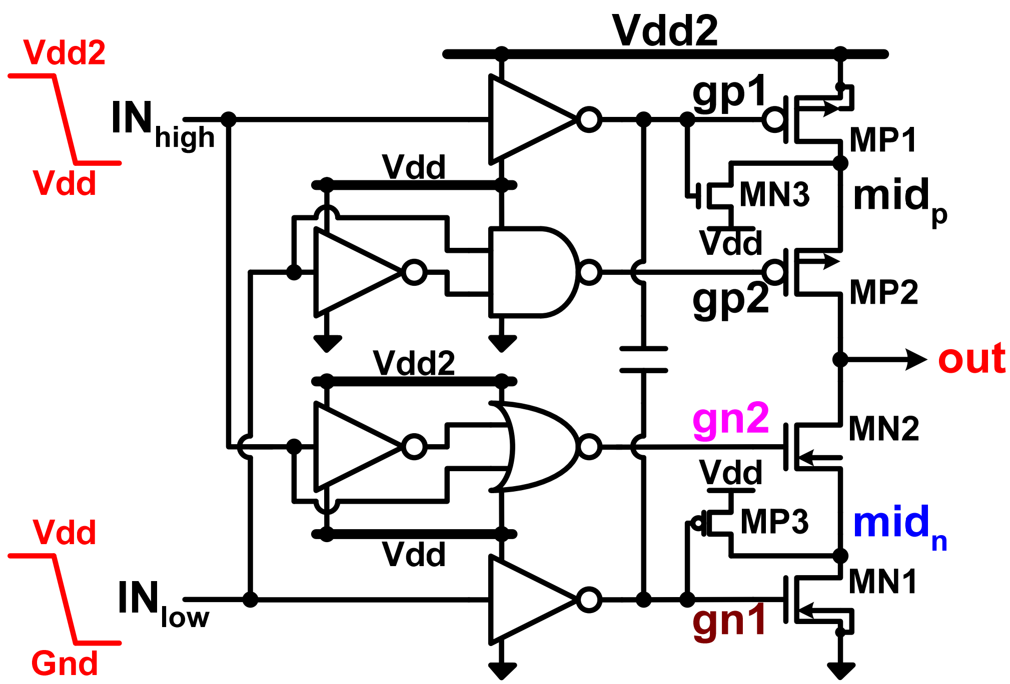
Pulsed-Cascode Output Stage

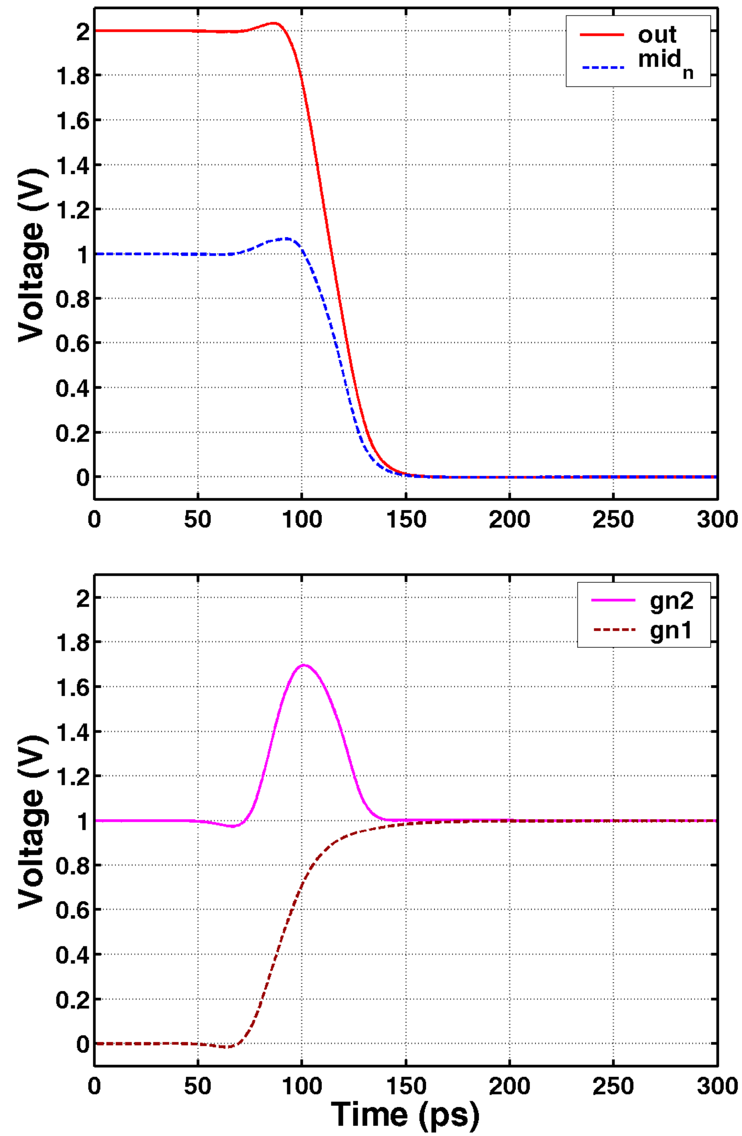


- Uses only two-transistor stack for maximum speed
- The cascode transistors gates are pulsed during a transistion to prevent Vds overstress

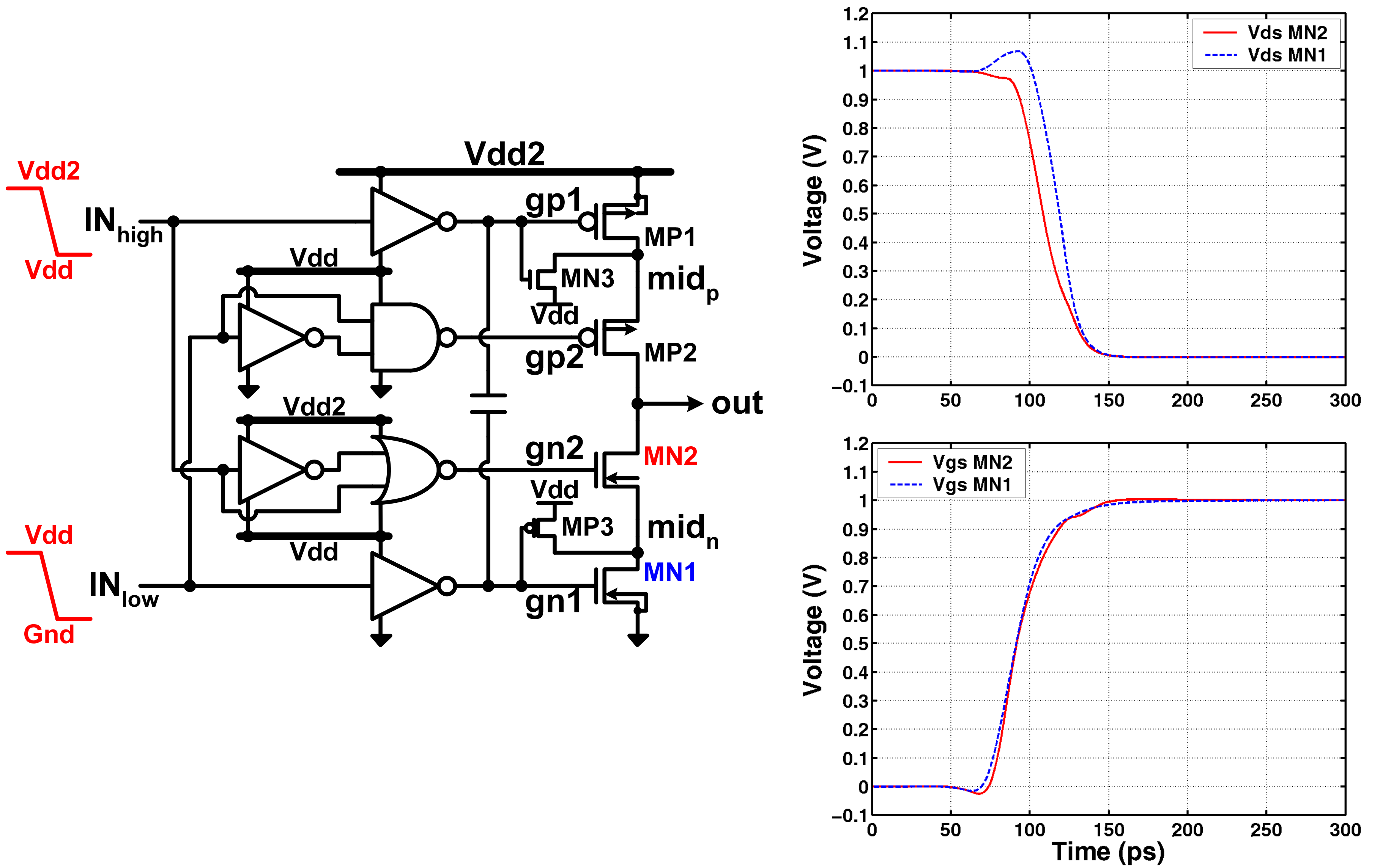
S. Palermo and M. Horowitz, "High-Speed Transmitters in 90nm CMOS for High-Density Optical Interconnects," ESSCIRC 2006.

Output Stage Waveforms

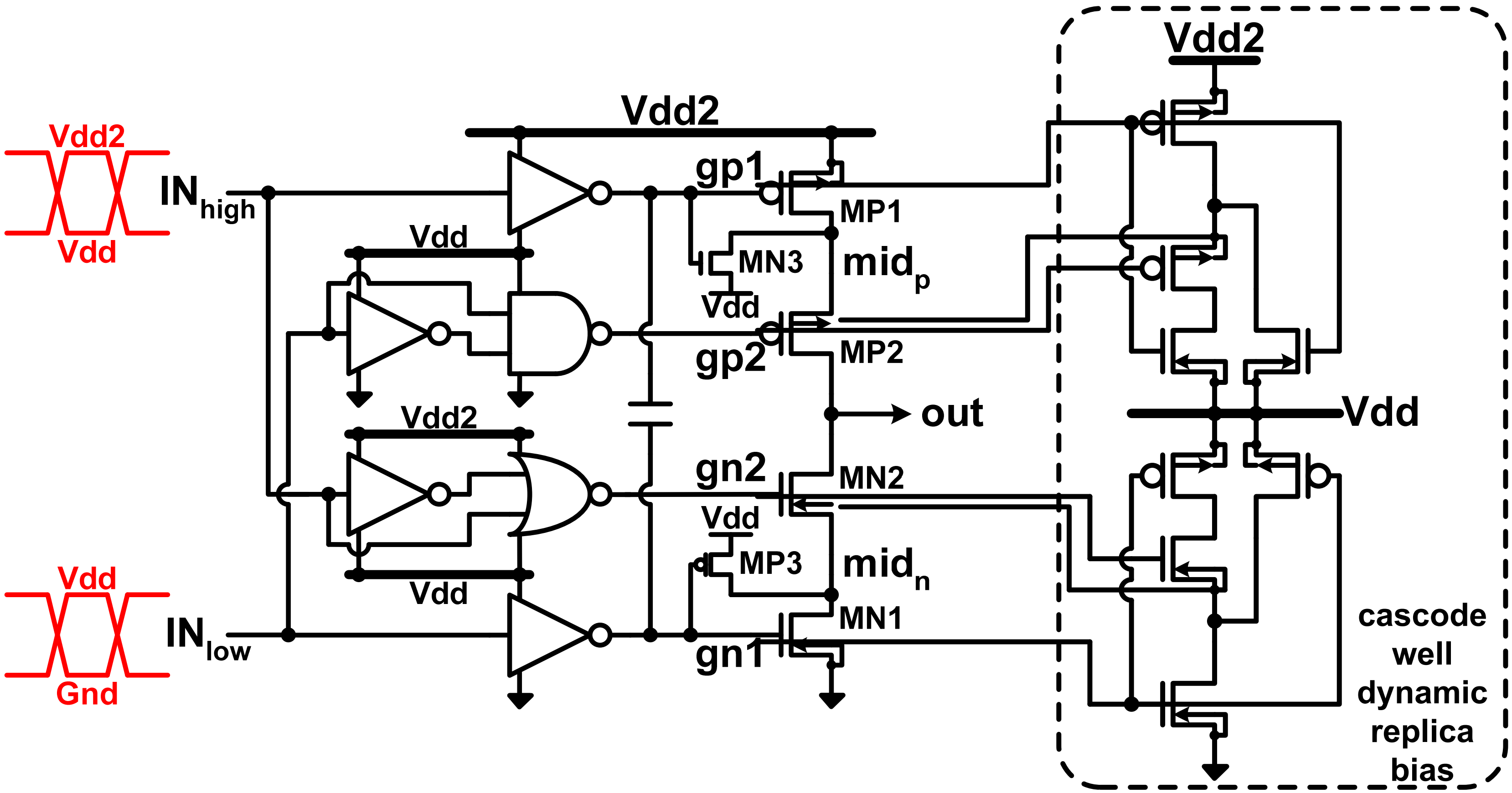




Output Stage Waveforms

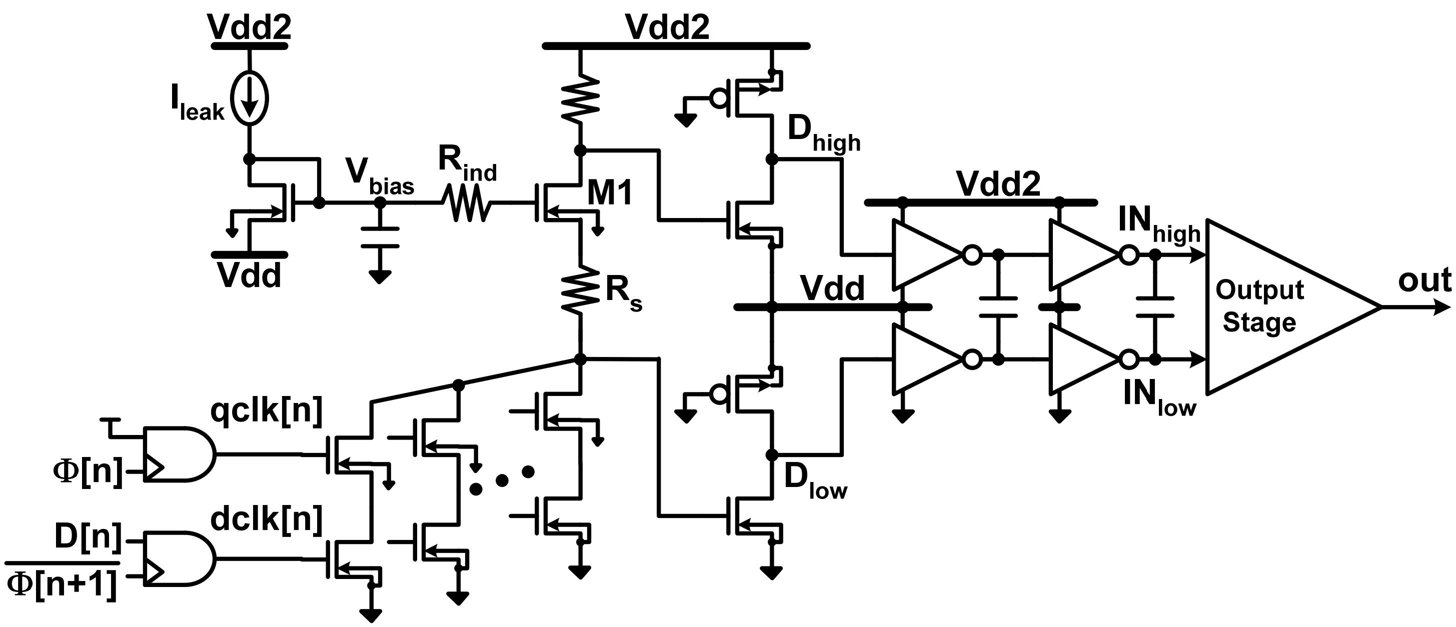


Pulsed-Cascode Output Stage



- Cascode body terminals dynamically biased to minimize body effect
- Issues
  - Voltage level shift
  - Delay matching high voltage path with standard voltage path

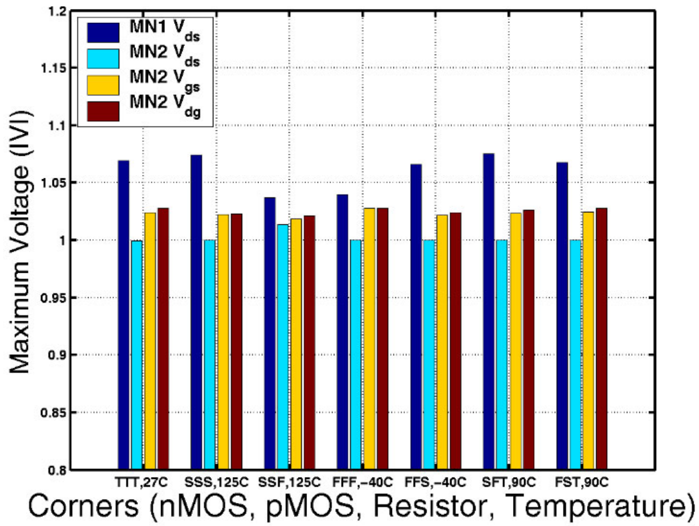
Modulator TX with Level-Shifting Multiplexer



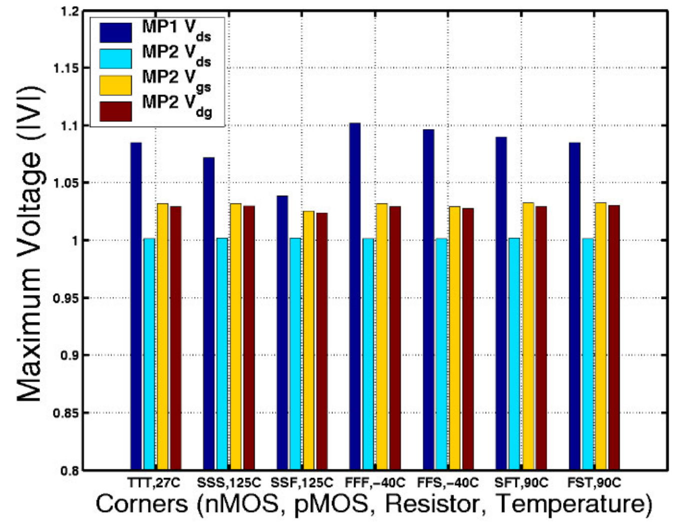
- Level-shifter combined with multiplexer
- Active inductive shunt peaking compensates multiplexer self-loading (reduces risetime by 37%)
- Slightly lower fan-out ratio in "high" signal path to compensate for level-shifting delay
- Delay Tracking
  - "High" path inverter nMOS in separate p-well
  - Metal fringe coupling capacitors perform skew compensation

Modulator Driver Reliability Simulations

Maximum nMOS Voltages

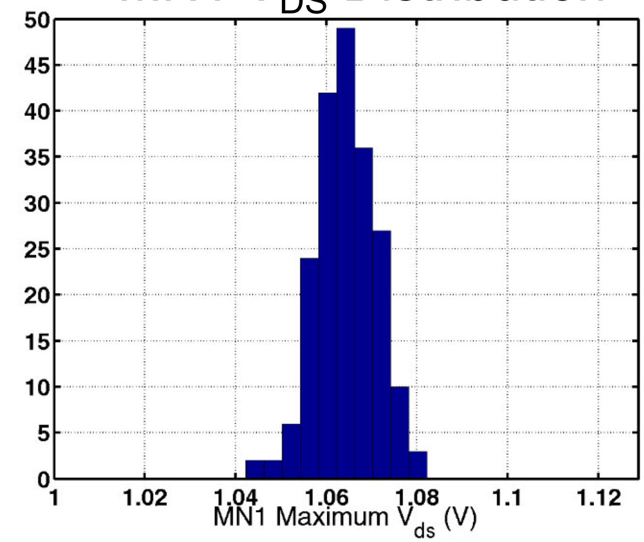


Maximum pMOS Voltages

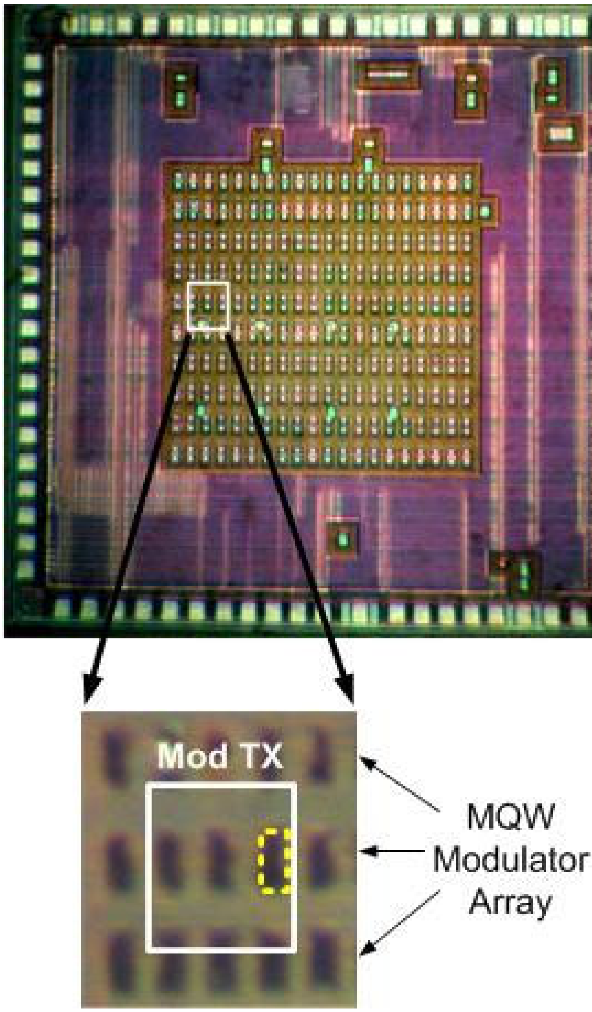


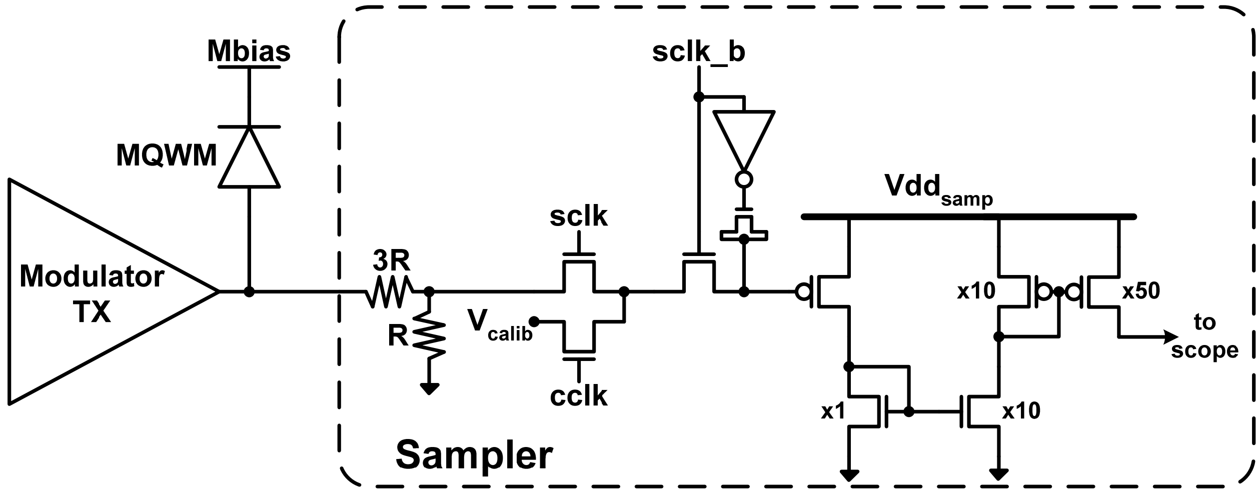
- Transient with random data
- Corner simulations show no output stage voltages exceed 11% of nominal Vdd
- Monte Carlo simulations show tight distributions (σ < 15mV)

MN1 V_{DS} Distribution



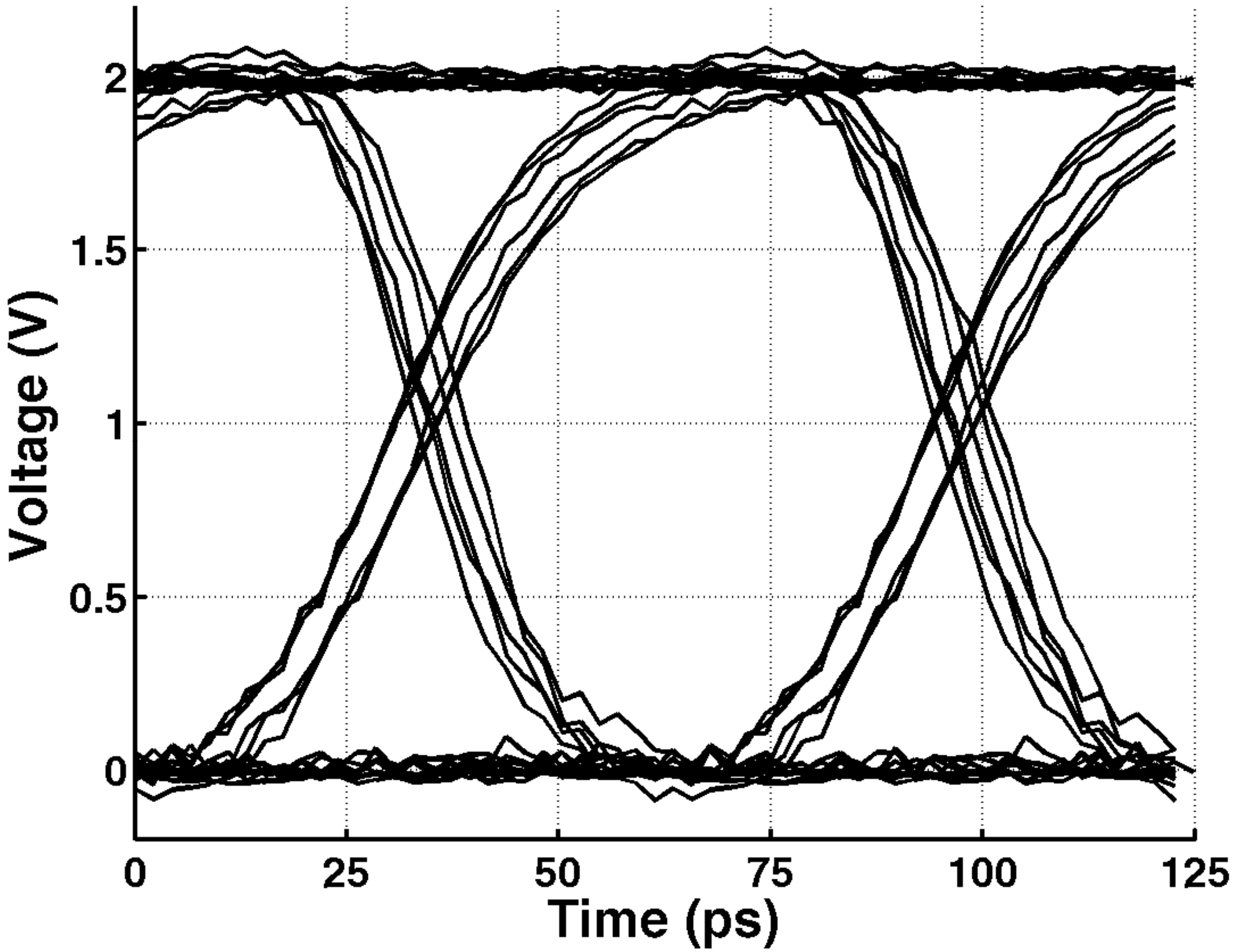
MQWM TX Testing





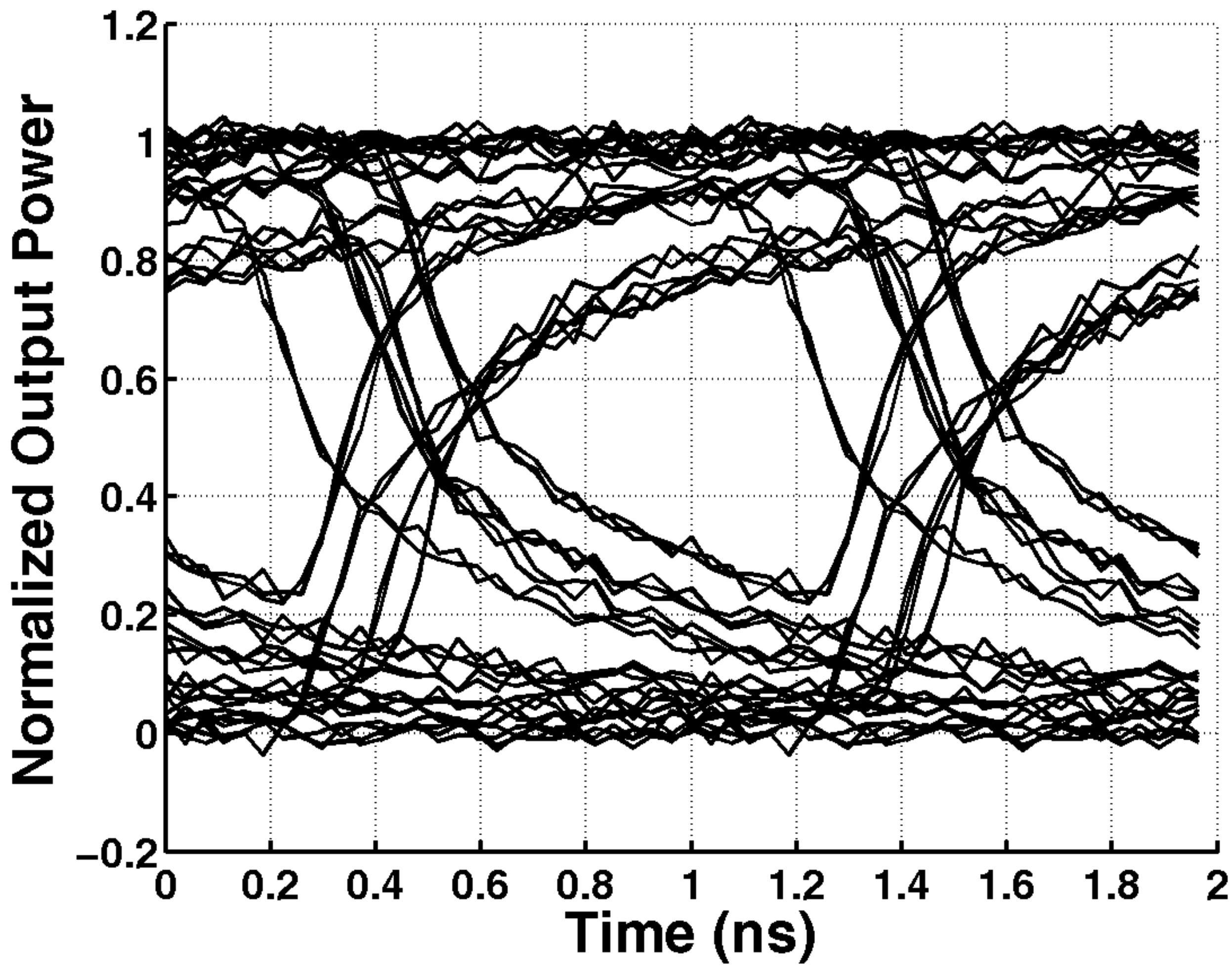
Electrical sampler at modulator transmitter output

Modulator Driver Electrical Eye Diagram



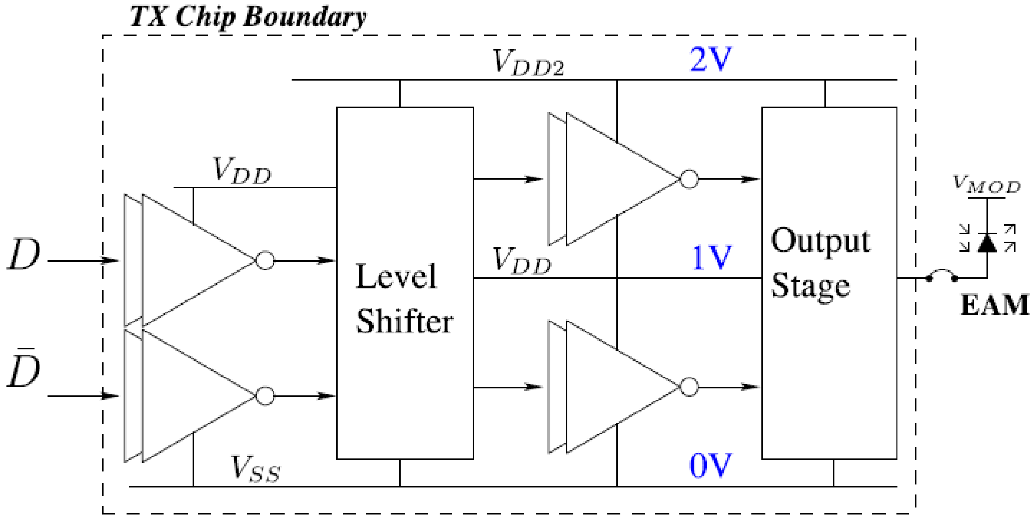
- 16Gb/s data subsampled at modulator driver output node

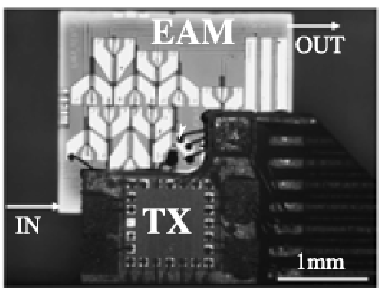
Modulator Driver Optical Eye Diagram

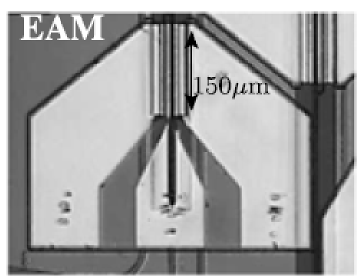


- Optical performance limited to ~1Gb/s by poor modulator contact design causing large series resistance

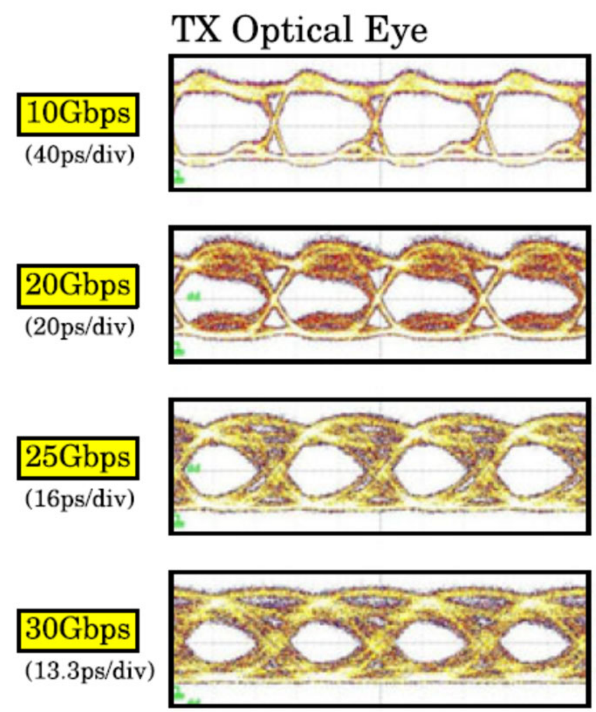
30Gb/s Lumped-Element EAM Driver







[Dupuis JLT 2015]



- Using a 5.4V reverse bias and 2Vpp dynamic swing to achieve 8dB ER
- Have ~7dB insertion loss

Next Time

- Ring Resonator Modulator (RRM) TX