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

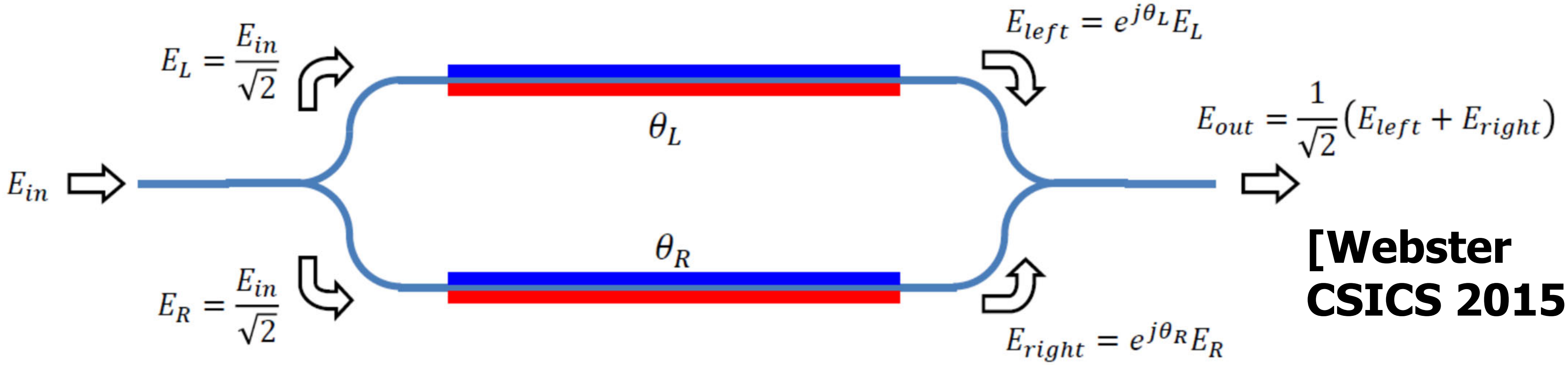
## Lecture 9: Mach-Zehnder Modulator Transmitters

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

# Announcements

- Homework 3 is due Apr 7
- Reading
  - Sackinger Chapter 8

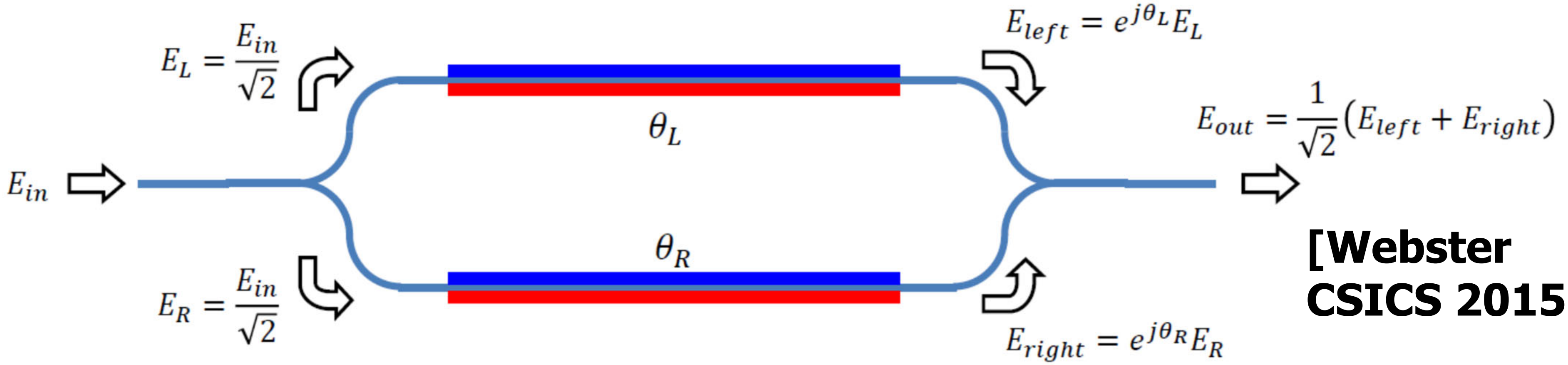
# Mach-Zehnder Modulator (MZM)




**[Webster CSICS 2015]**

- An optical interferometer is formed with the incoming light split, experiencing phase shifts through the two paths, and then recombined
- If the phase shift between the two waves is 0°, then there is maximum constructive interference and the output intensity is highest (ideal logic 1)
- If the phase shift between the two waves is 180°, then there is maximum destructive interference and the output intensity is lowest (ideal logic 0)
- An MZM changes the relative phase between the two paths with a modulation voltage via the electrooptic effect, producing the modulated output signal

# Ideal MZM Response




**[Webster CSICS 2015]**

- Assuming no loss and a perfect 50/50 splitter/combiner

$$\Delta\phi = \frac{(\theta_R - \theta_L)}{2} \qquad \phi = \frac{(\theta_R + \theta_L)}{2}$$

Field Response

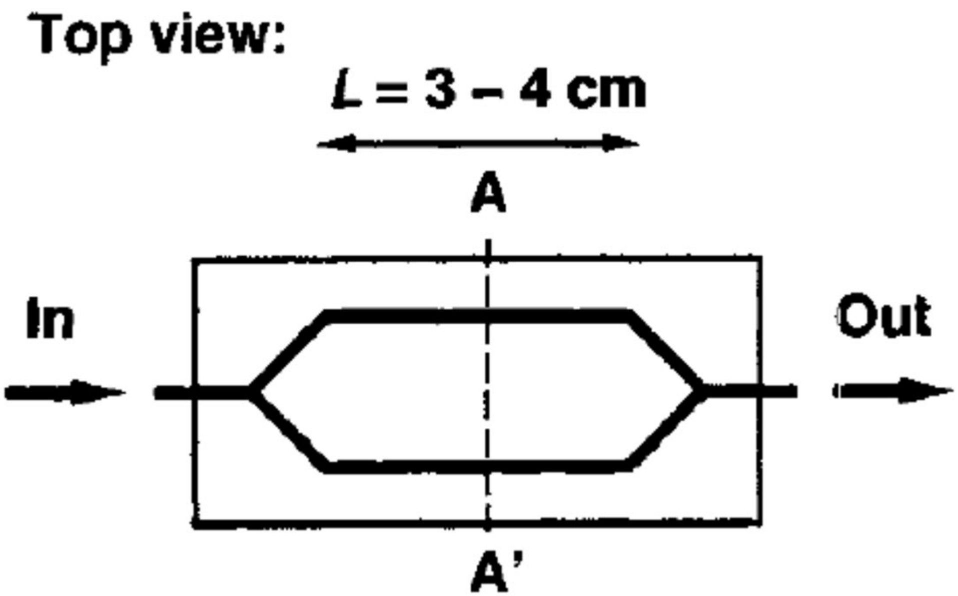
$$E_{out} = E_{in} \cos(\Delta\phi) e^{j\phi}$$

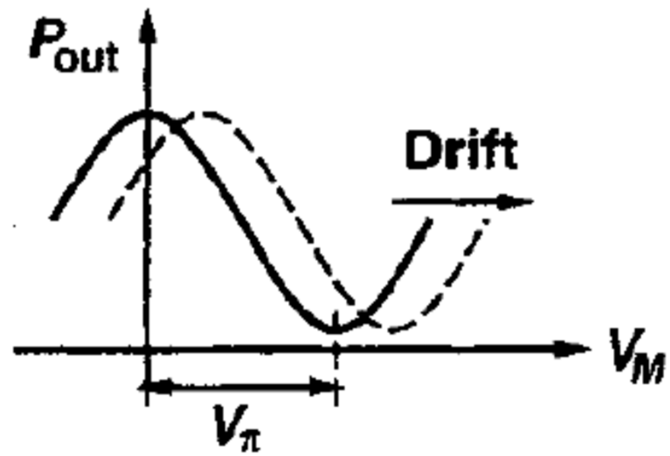
Intensity Response

$$P_{out} = |E_{out}|^2 = \frac{1}{2}|E_{in}|^2 [1 + \cos(\theta_R - \theta_L)]$$

$$\frac{P_{out}}{P_{in}} = \frac{1}{2}[1 + \cos(\theta_R - \theta_L)]$$

# Ideal MZM Response

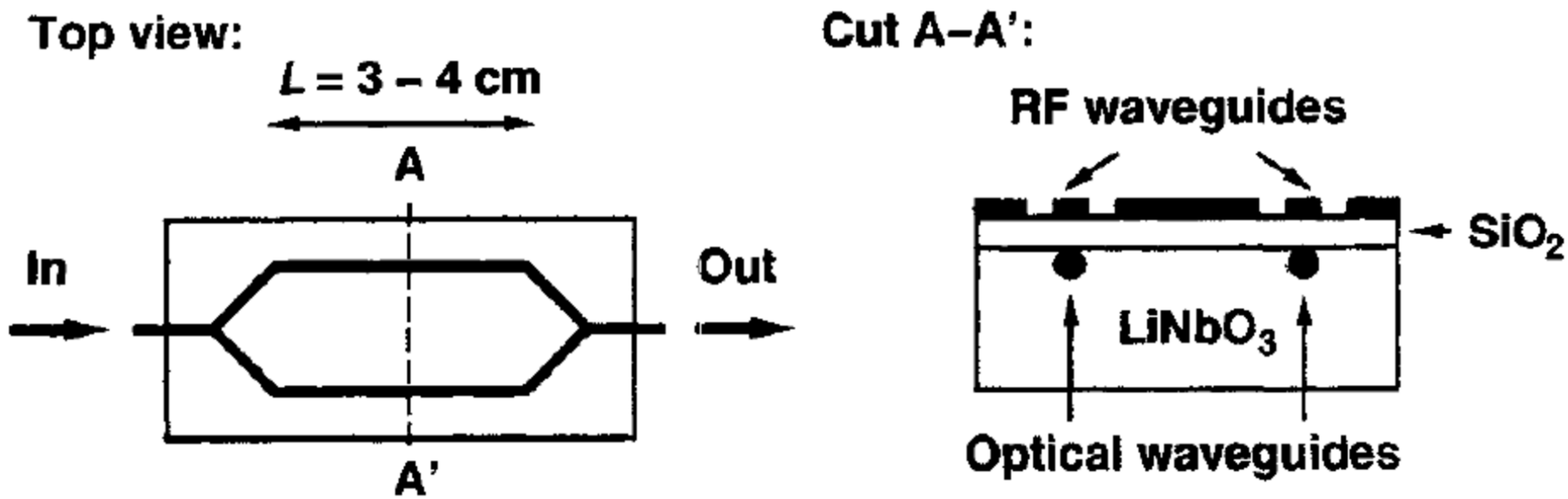



$$\frac{P_{out}}{P_{in}} = \frac{1}{2}\left[1+\cos(\theta_R - \theta_L)\right] = \frac{1}{2}\left[1+\cos\left(\pi \cdot \frac{V_M}{V\pi}\right)\right]$$

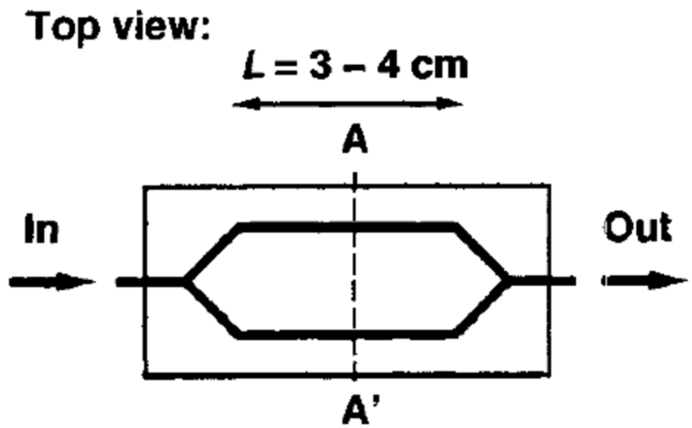
Here $V_M$ is the differential voltage applied between the two input ports and $V_\pi$ is the voltage necessary for $\pi$ phase shift, also called the switching voltage.

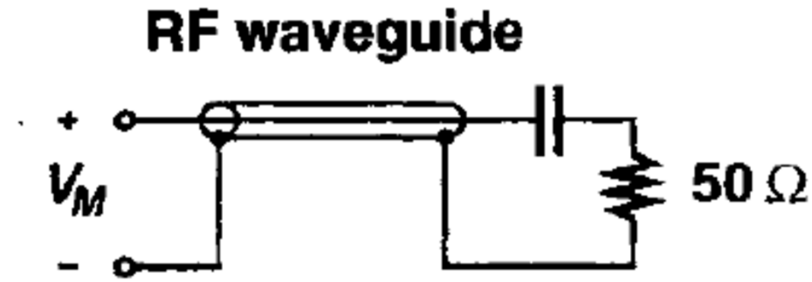
# Single or Dual-Drive




- Single-Drive MZM
  - Only one are is driven in a single-ended manner
  - While only requiring a single high-speed input signal, there is generally some chirp in the output signal
  - Need to apply the full $V_{\Pi}$ to one are to get maximum extinction ratio
- Dual-Drive MZM
  - Both arms are driven in a differential/push-pull manner
  - This ideally results in no chirp at the output
  - Only need to apply $\pm V_{\Pi}/2$ on the two arms to get maximum extinction ratio

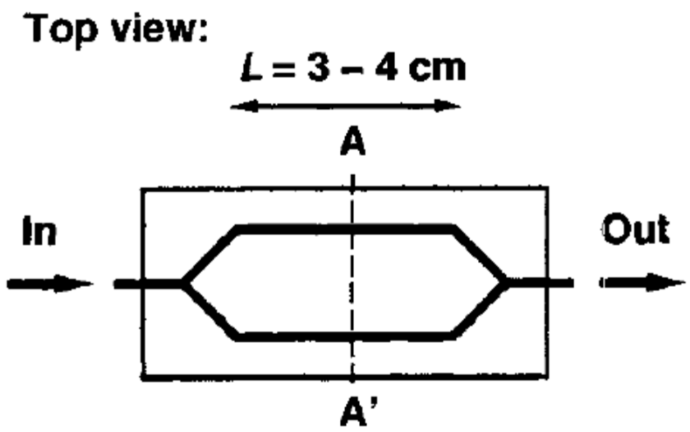
# $V_{\Pi}$*L Product




- The amount of phase shift generated by an MZM is proportional to voltage applied and the length of the phase shifter
- Thus, an MZM figure of merit is the $V_{\Pi}$*L product
- Typical values
  - Lithium Niobate: 14Vcm
  - Silicon (Depletion-Mode): 4Vcm
  - Silicon (MOS Capacitor): 0.2Vcm
- These large VP*L products lead to long controlled-impedance electrodes which must be terminated
- A key challenge is matching the propagation speed of the electrical modulation signal with the optical beam

# Chirp Parameter




$$\alpha = \frac{v_{M1}^{pp} + v_{M2}^{pp}}{v_{M1}^{pp} - v_{M2}^{pp}}$$

where $v_{M1}^{pp}$ and $v_{M2}^{pp}$ are the voltage swings on the two modulator arms.

With differential signaling $v_{M1}^{pp} = -v_{M2}^{pp}$ and the chirp is ideally zero.

If $v_{M1}^{pp} < -v_{M2}^{pp}$ then we can actually have negative chirp and potential pulse compression when passed through a fiber with positive $D$

If $v_{M1}^{pp} = v_{M2}^{pp}$, then we get a purely phase modulated signal and the MZM can be used for phase modulation (QPSK), rather than amplitude modulation.

# Silicon Free Carrier Plasma Dispersion Effect

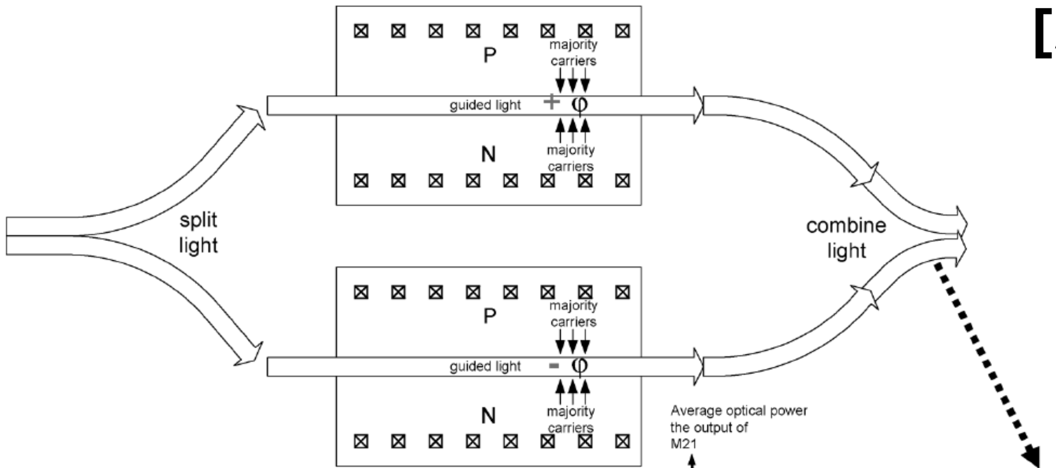
- The refractive index of silicon can be changed through the free-carrier plasma dispersion effect where the electron and hole densities change the refractive index
- Unfortunately, this also changes the waveguide's absorption (loss)
- This effect is utilized for all present high-speed silicon photonic modulators

$$\left.\begin{aligned}\Delta n &= \Delta n_e + \Delta n_h = -8.8\times10^{-22}(\Delta N_e) - 8.5\times10^{-18}(\Delta N_h)^{0.8}\\ \Delta\alpha &= \Delta\alpha_e + \Delta\alpha_h = 8.5\times10^{-18}(\Delta N_e) + 6.0\times10^{-18}(\Delta N_h)\end{aligned}\right\}\ \lambda\text{=1550nm}$$

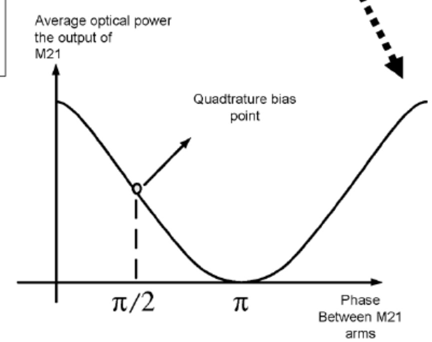
$$\left.\begin{aligned}\Delta n &= \Delta n_e + \Delta n_h = -6.2\times10^{-22}(\Delta N_e) - 6.0\times10^{-18}(\Delta N_h)^{0.8}\\ \Delta\alpha &= \Delta\alpha_e + \Delta\alpha_h = 6.0\times10^{-18}(\Delta N_e) + 4.0\times10^{-18}(\Delta N_h)\end{aligned}\right\}\ \lambda\text{=1310nm}$$

# Silicon Depletion-Mode MZM

**[Analui JSSC 2006]**



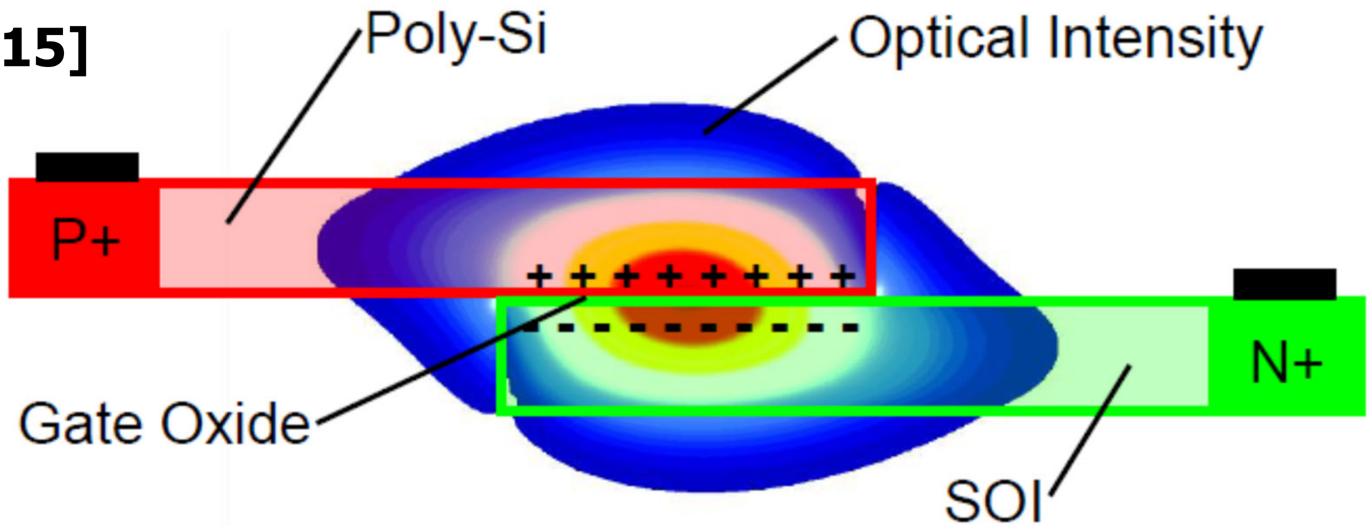

$$\frac{P_{out}}{P_{in}} = \frac{1+\cos\Delta\varnothing}{2}$$




- Here the silicon waveguide is doped as a PN junction
- The depletion region is modulated as a function of the applied reverse bias voltage
- The resultant change in the carrier density within the depletion region causes the refractive index to change

# MOS Capacitor Accumulation Mode MZM

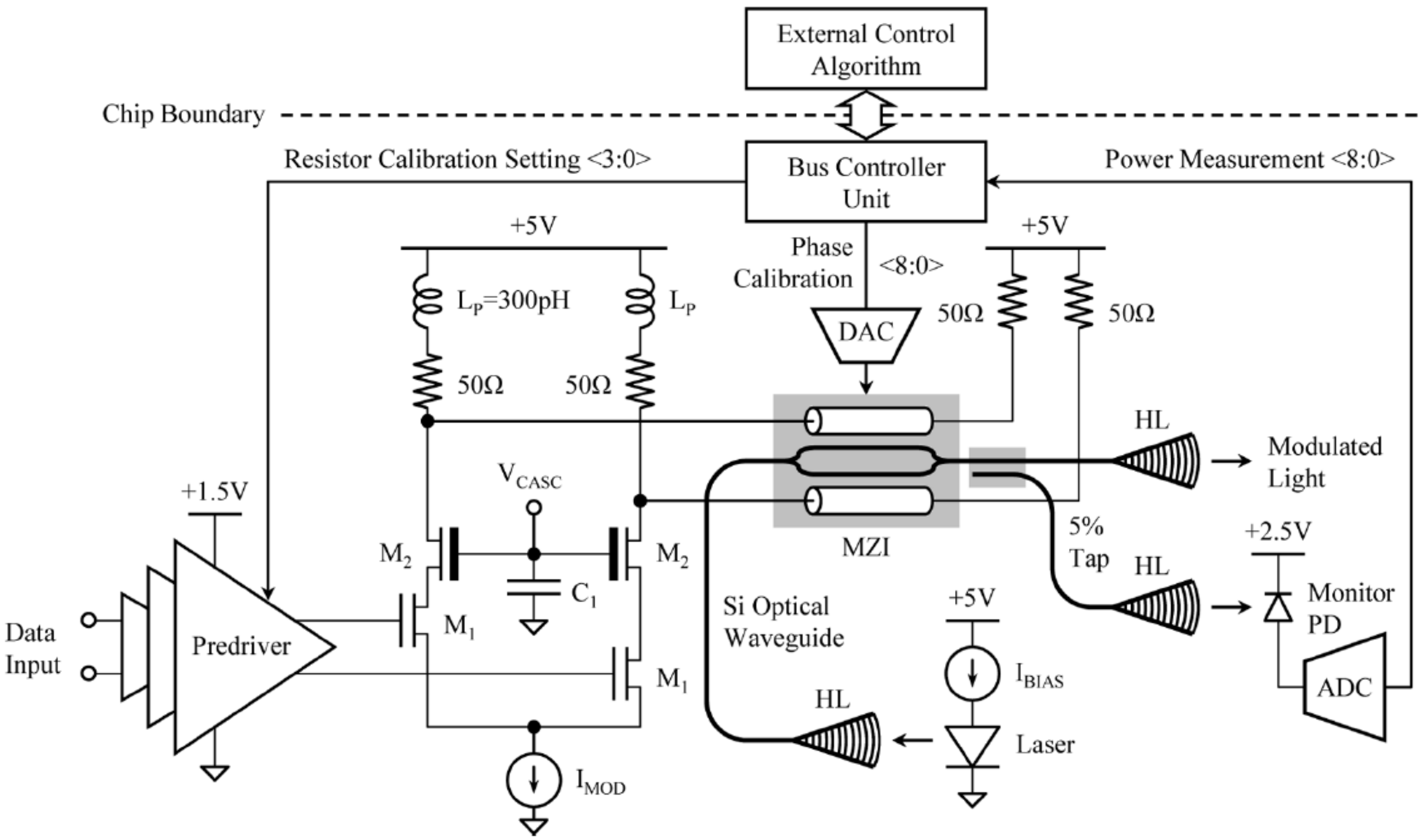
**[Webster CSICS 2015]**



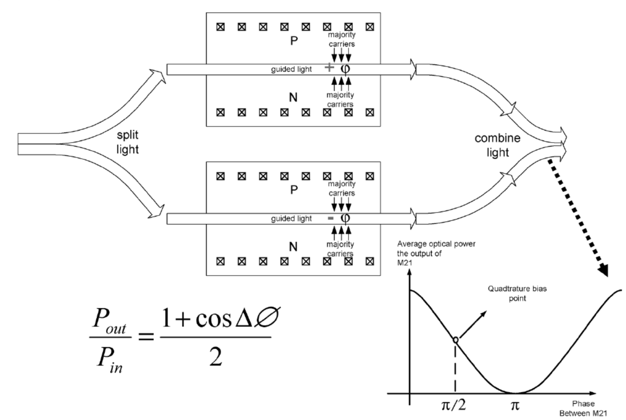

- With a MOS capacitor structure, a change in the accumulation carrier density occurs with the applied gate voltage
- The resultant change in the carrier density within the MOS capacitor region causes the refractive index to change
- Very large changes in charge density can be achieved!

# Traveling-Wave MZM Driver

[Analui JSSC 2006]



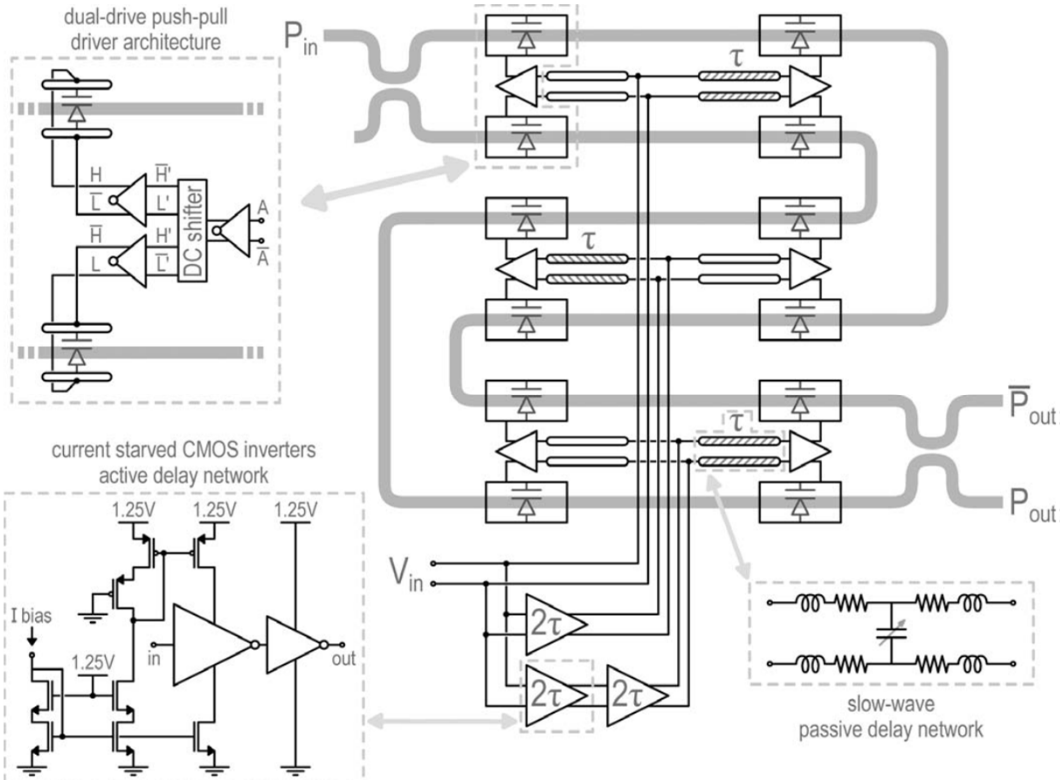

- Depletion-mode MZM is driven with a $5V_{ppd}$ signal

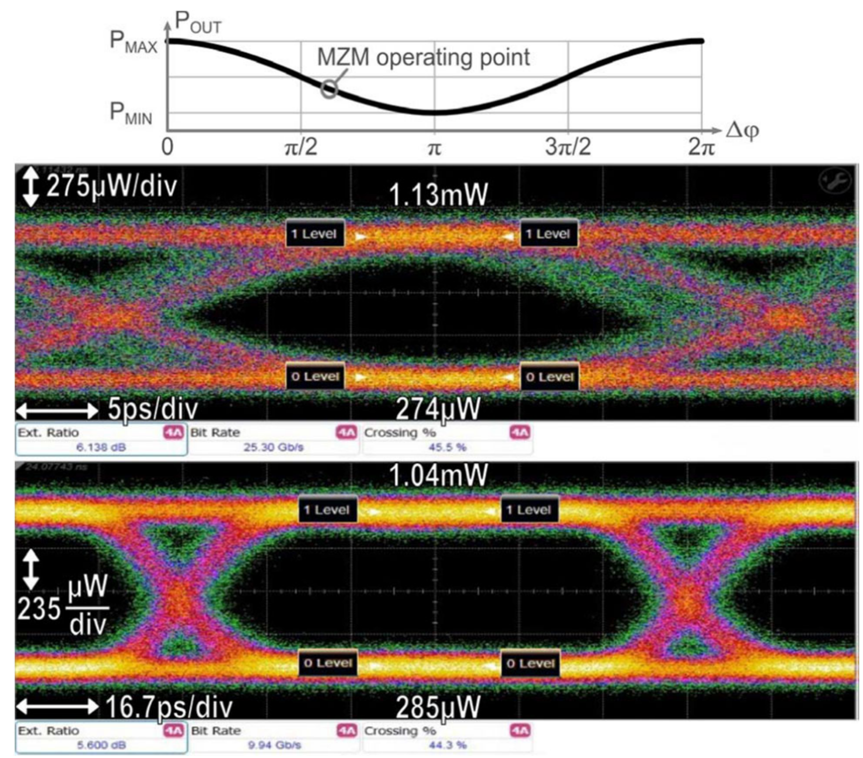



$$\frac{P_{out}}{P_{in}} = \frac{1+\cos\Delta\varnothing}{2}$$

# Distributed MZM Driver

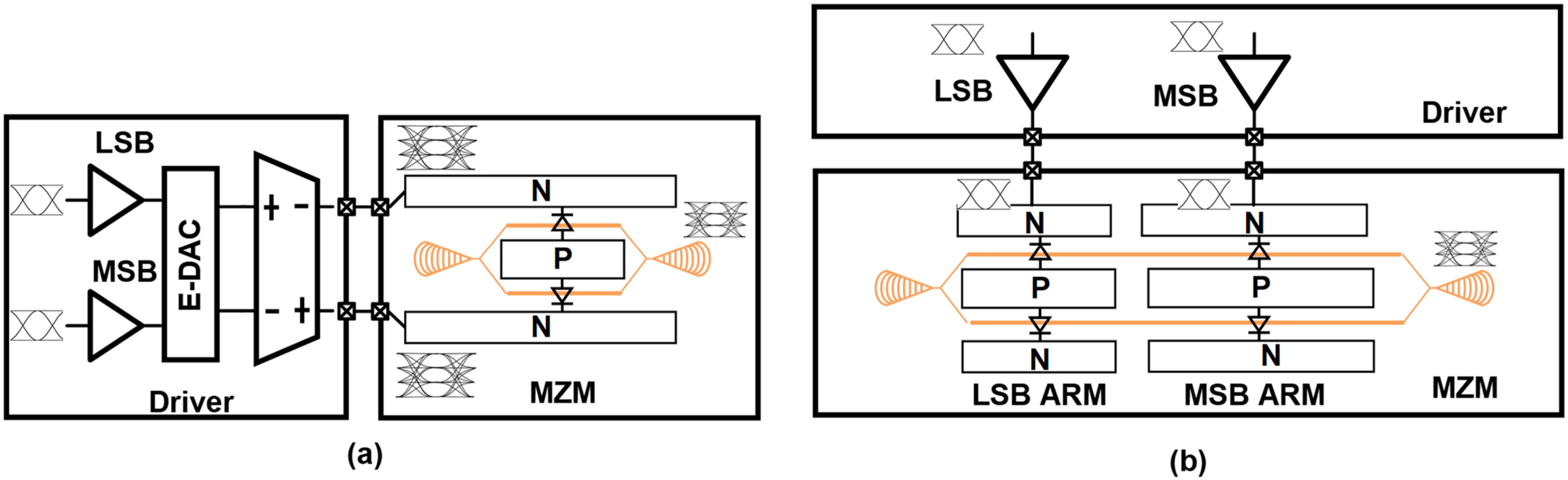
**[Cignoli ISSCC 2015]**



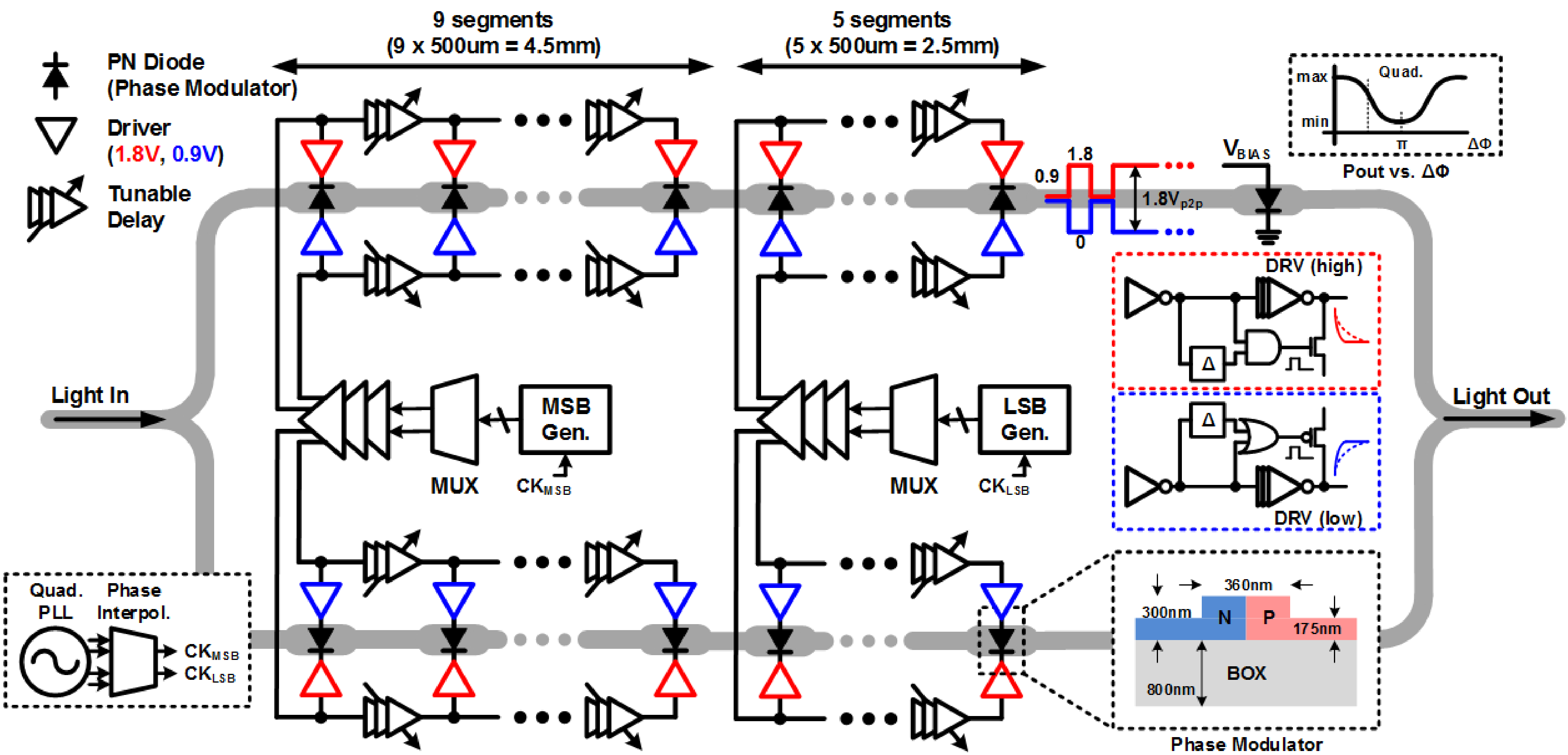

- Allows for CMOS style drivers
- Well suited for a monolithic silicon photonic process
- Hybrid integration requires may pad connections between CMOS/silicon photonic die

# PAM4 Level Generation w/ MZMs



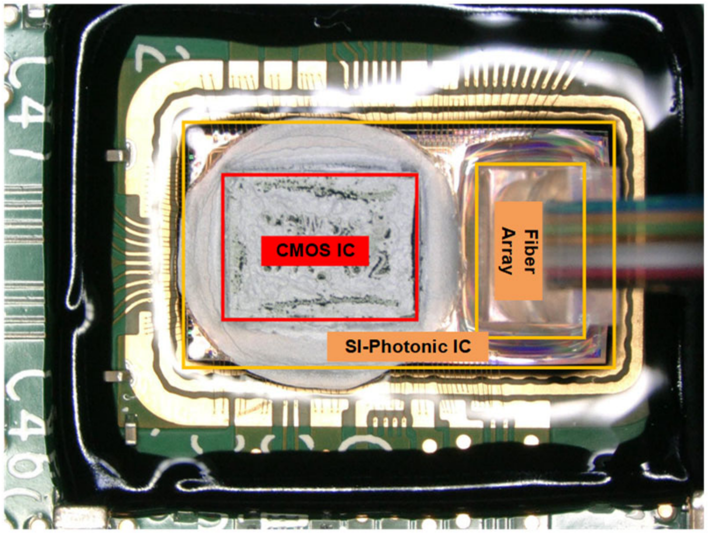

- E-DAC PAM4 TX
  - PAM4 driver bandwidth and swing limitation
  - Multi current/voltage level
- O-DAC PAM4 TX
  - Velocity mismatch between LSB and MSB
  - Multi driver design

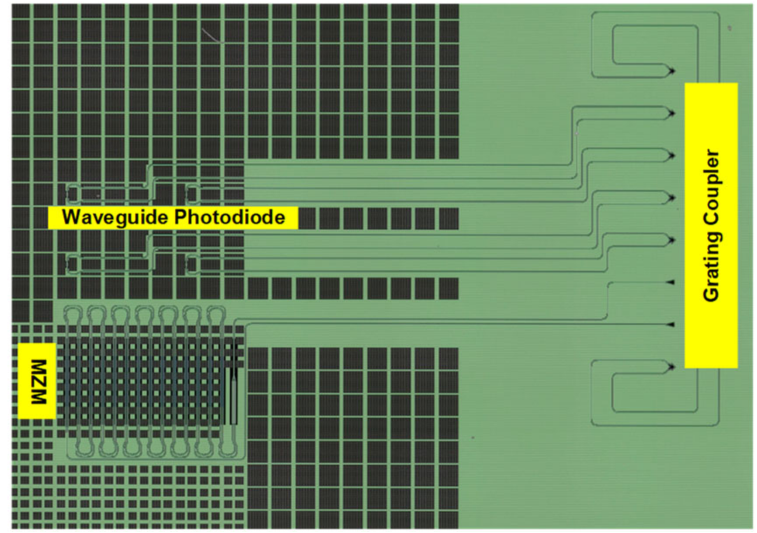
# Optical DAC NRZ/PAM4 Reconfigurable MZM TX



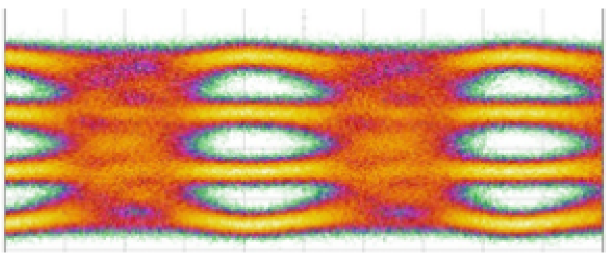

- 5 LSB segments and 9 MSB segments

# 56Gb/s PAM4 16nm FinFET CMOS Prototype

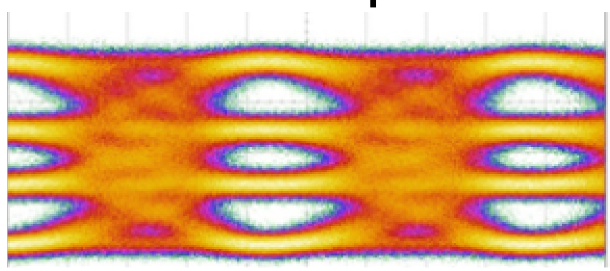


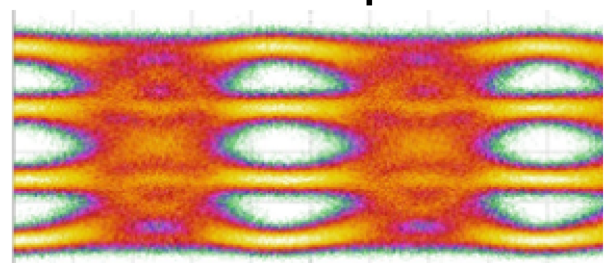

150uw/div 8ps/div



150uw/div 8ps/div



150uw/div 8ps/div



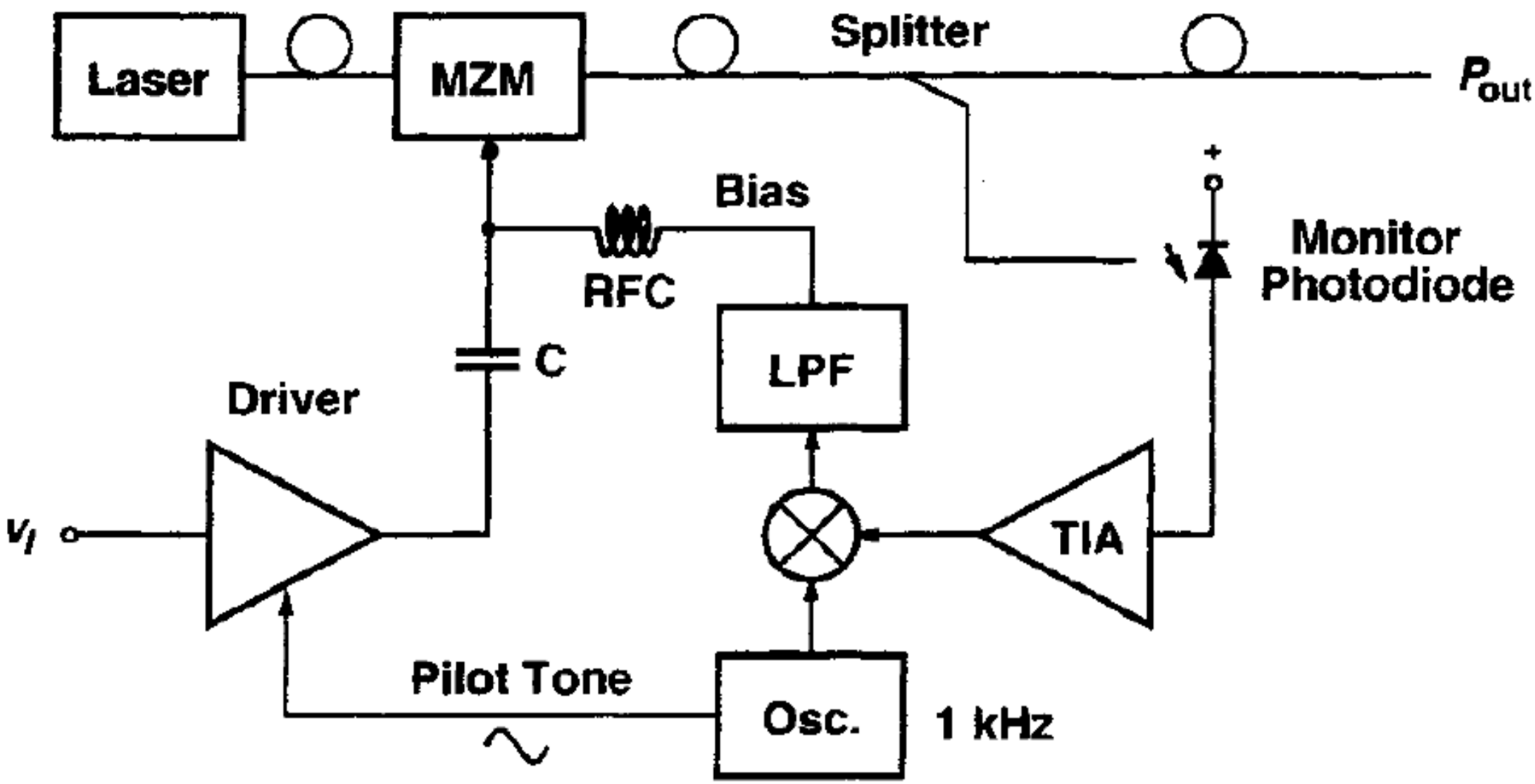
| | Segment setting | ER | RLM | EYE width | Eye height |
|---|---|---|---|---|---|
| (a) | 3 LSB+6 MSB | 6.35dB | 0.942 | 5.12ps | 11.6uW |
| (b) | 4 LSB+7 MSB | 8.14dB | 0.896 | 5.01ps | 4.6uW |
| (c) | 4 LSB+8 MSB | 8.46dB | 0.944 | 5.7ps | 18.4uW |

# MZM Transmitter Performance Summary

| References | This Work | Cignoli ISSCC 2015 | Temporiti ISSCC 2016 | Qi OFC 2016 | Xiong Optica 2016 |
|---|---|---|---|---|---|
| Data Rate (Gb/s) | 56 | 25 | 56 | 50 | 56 |
| Modulation | NRZ/PAM4 | NRZ | NRZ | NRZ/PAM4 | PAM4 |
| Modulator Structure | SE | SE | TW | TW | TW |
| Integration Technology | Copper Pillar | Copper Pillar | Copper Pillar | Wire Bond | Monolithic |
| MZM Length(mm) | 7 | 3 | 3 | NA | 3 |
| Test Pattern | PRBS 23 | PRBS 7 | PRBS 31 | PRBS 31 | PRBS 23 |
| Extinction Ratio (dB) | 9.5 | 4-6 | 2.5 | 5.6 | 6 |
| Power (mW) | 708* | 275 | 300 | 613 | 135** |
| Power Efficiency (pJ/bit) | 12.6 | 11 | 5.35 | 12.26 | 2.7 |
| Technology | 16nm FinFET | 65-nm CMOS | 55-nm BiCMOS | 65-nm CMOS | 90-nm CMOS SOI |

* Clocking and data serialization and digital backends power are included
** Power Consumption at 50Gbps

# Automatic Bias Control



# Next Time

- Electroabsorption Modulator (EAM) TX