ECEN721: Optical Interconnects Circuits and Systems
Spring 2024

Lecture 9: Mach-Zehnder Modulator Transmitters

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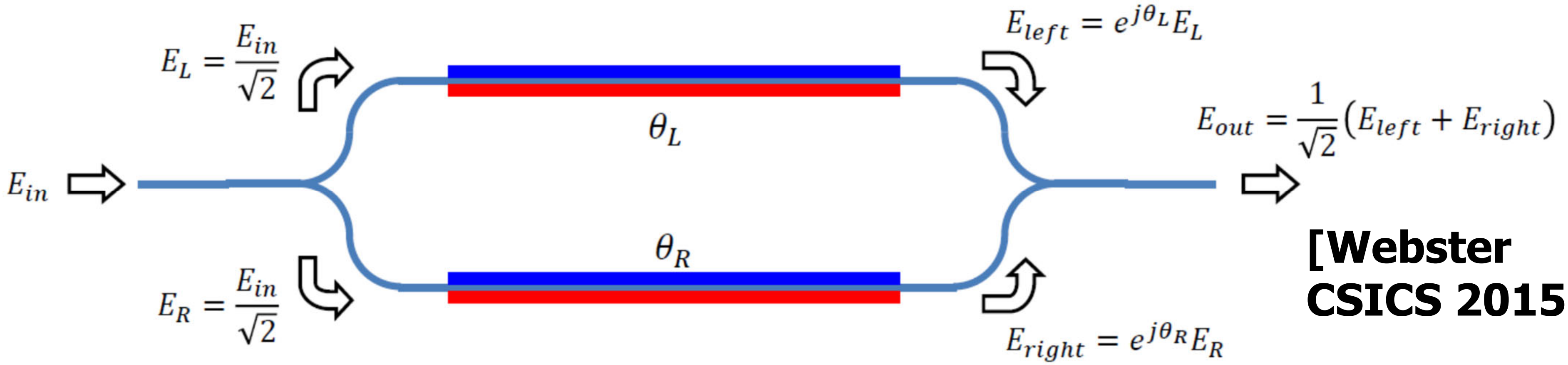
Announcements

- Homework 3 is due today

- Reading
  - Sackinger Chapter 8

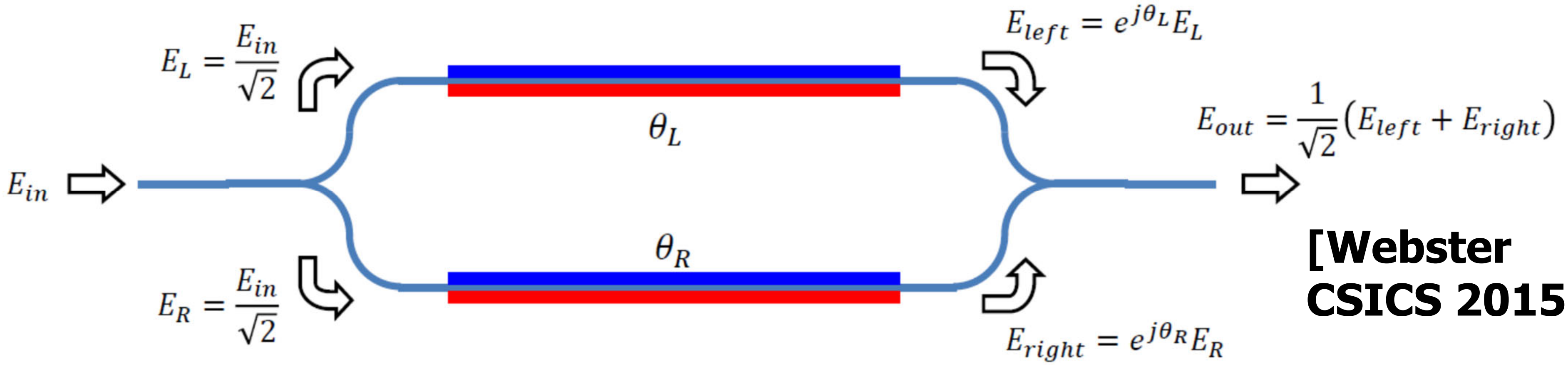
Mach-Zehnder Modulator (MZM)



[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

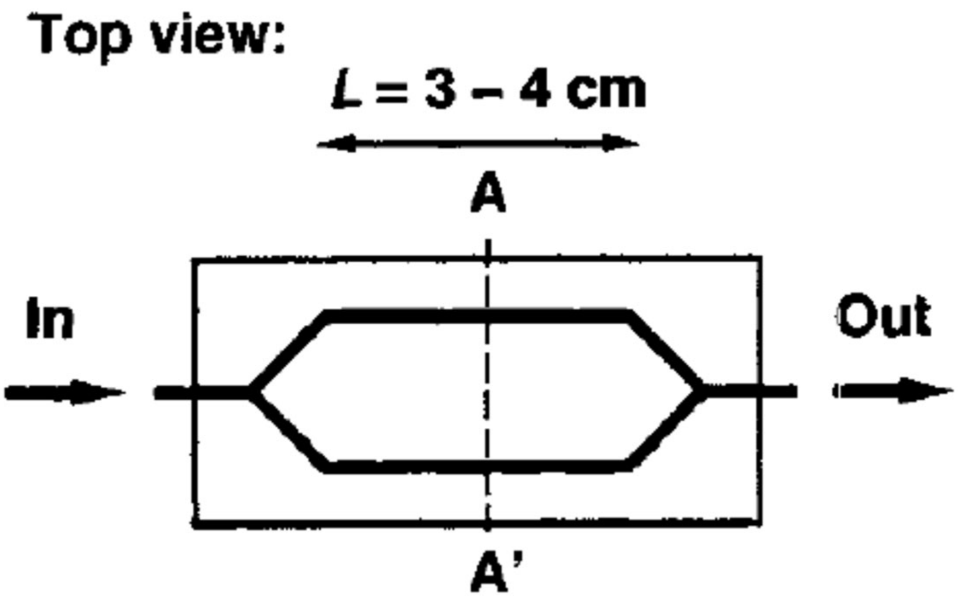
$$E_{out} = E_{in} \cos(\Delta\phi) e^{j\phi}$$

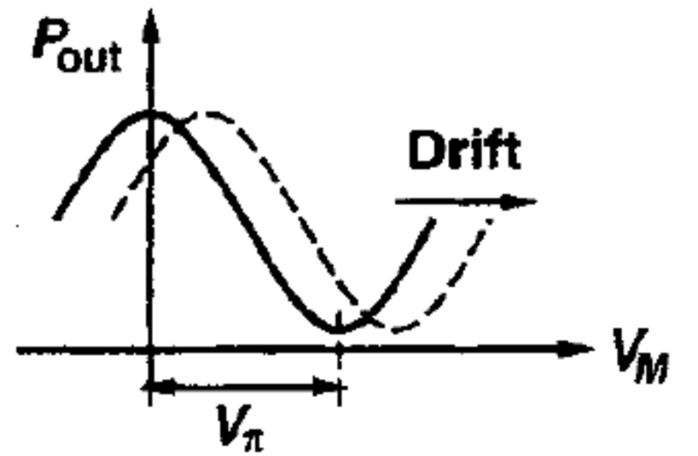
Intensity Response

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

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

Ideal MZM Response

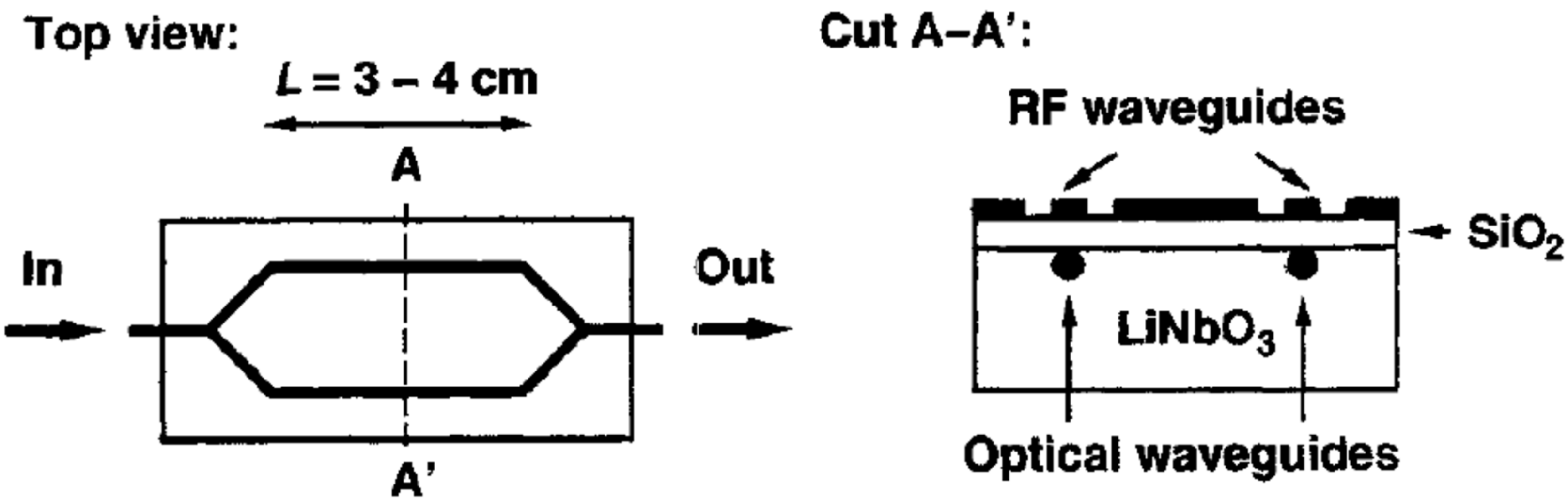




$$\frac{P_{out}}{P_{in}} = \frac{1}{2}\left[1+\cos(\theta_R - \theta_L)\right] = \frac{1}{2}\left[1+\cos\left(\pi \cdot \frac{V_M}{V\pi}\right)\right]$$

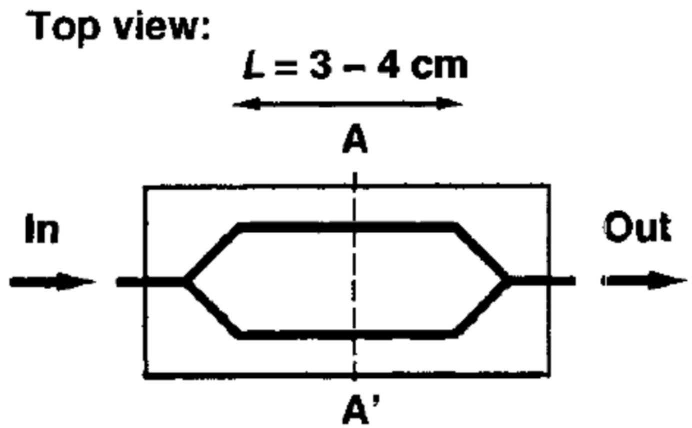
Here V_M is the differential voltage applied between the two input ports and V_π is the voltage necessary for π phase shift, also called the switching voltage.

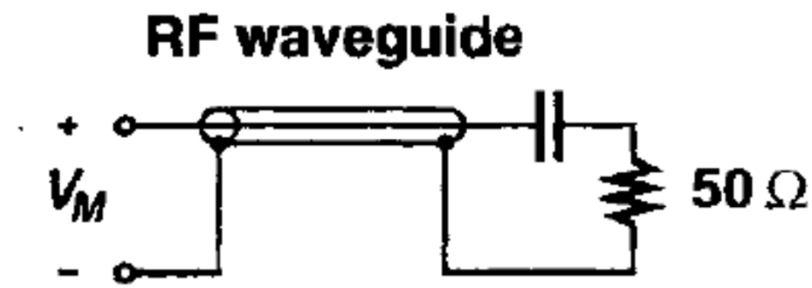
Single or Dual-Drive



- 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_{Π} 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

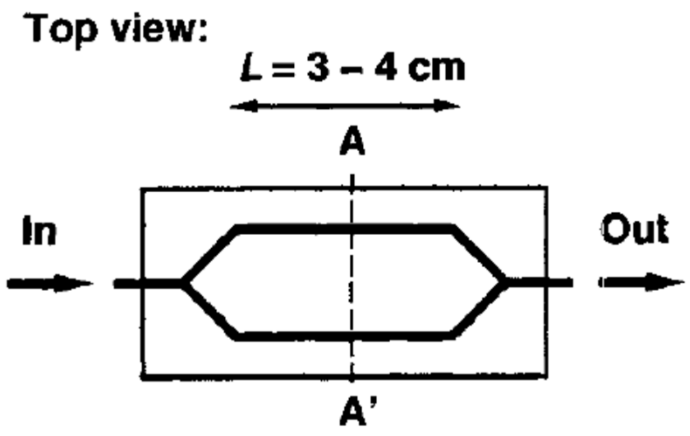
V_{Π}*L Product





- 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_{Π}*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

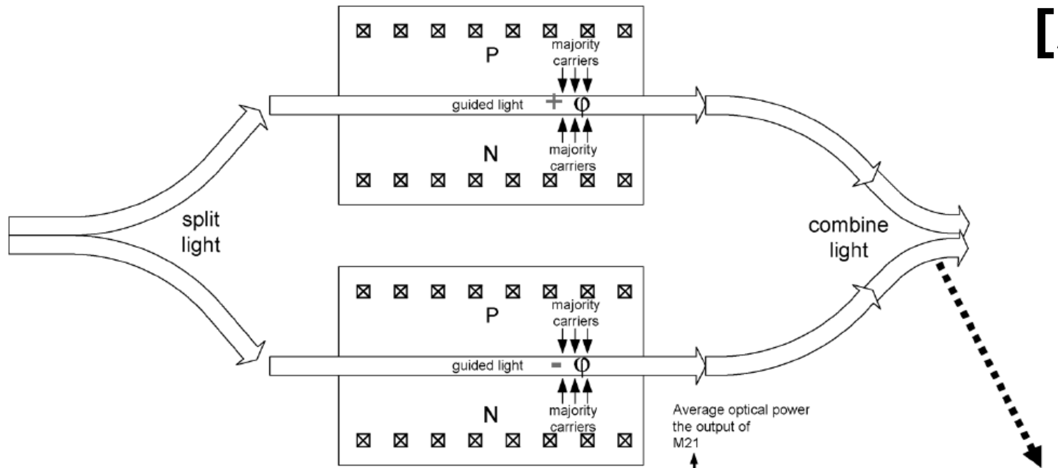
- The refractive index of silicon can be changed through the free-carrier plasma dispersion effect where the electron and hole densities change the refractive index
- Unfortunately, this also changes the waveguide's absorption (loss)
- This effect is utilized for all present high-speed silicon photonic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

$$\left.\begin{aligned}\Delta n &= \Delta n_e + \Delta n_h = -8.8 \times 10^{-22}(\Delta N_e) - 8.5 \times 10^{-18}(\Delta N_h)^{0.8} \\ \Delta \alpha &= \Delta \alpha_e + \Delta \alpha_h = 8.5 \times 10^{-18}(\Delta N_e) + 6.0 \times 10^{-18}(\Delta N_h)\end{aligned}\right\} \lambda=1550\text{nm}$$

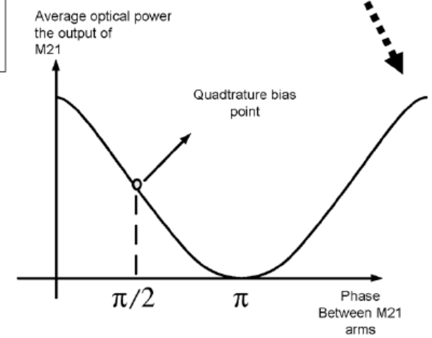
$$\left.\begin{aligned}\Delta n &= \Delta n_e + \Delta n_h = -6.2 \times 10^{-22}(\Delta N_e) - 6.0 \times 10^{-18}(\Delta N_h)^{0.8} \\ \Delta \alpha &= \Delta \alpha_e + \Delta \alpha_h = 6.0 \times 10^{-18}(\Delta N_e) + 4.0 \times 10^{-18}(\Delta N_h)\end{aligned}\right\} \lambda=1310\text{nm}$$

Silicon Depletion-Mode MZM

[Analui JSSC 2006]



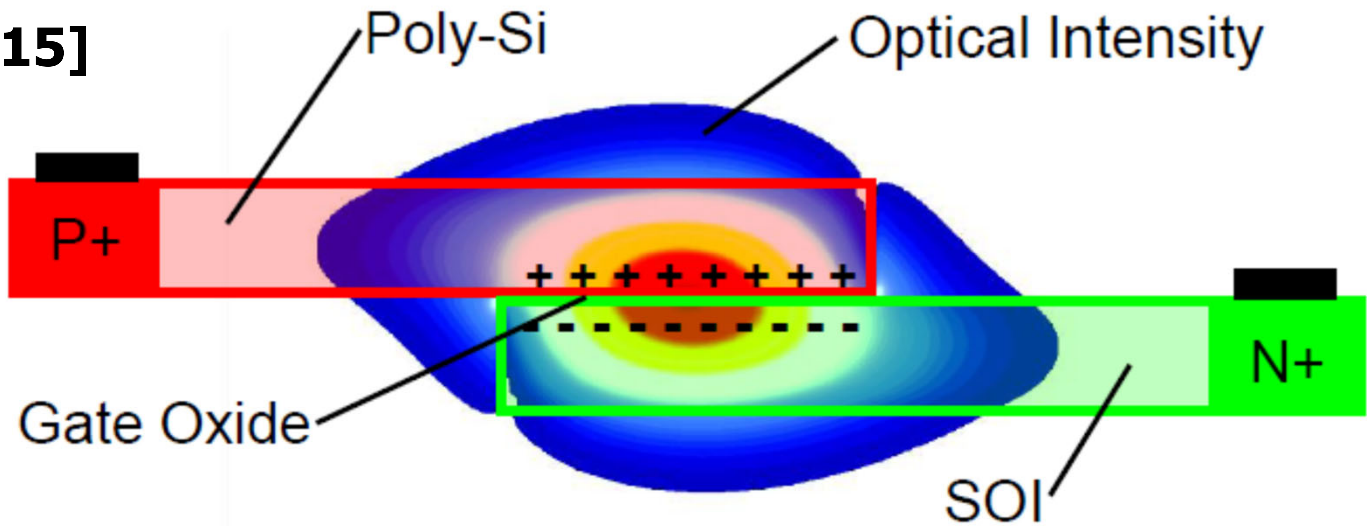
$$\frac{P_{out}}{P_{in}} = \frac{1+\cos\Delta\varnothing}{2}$$



- 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

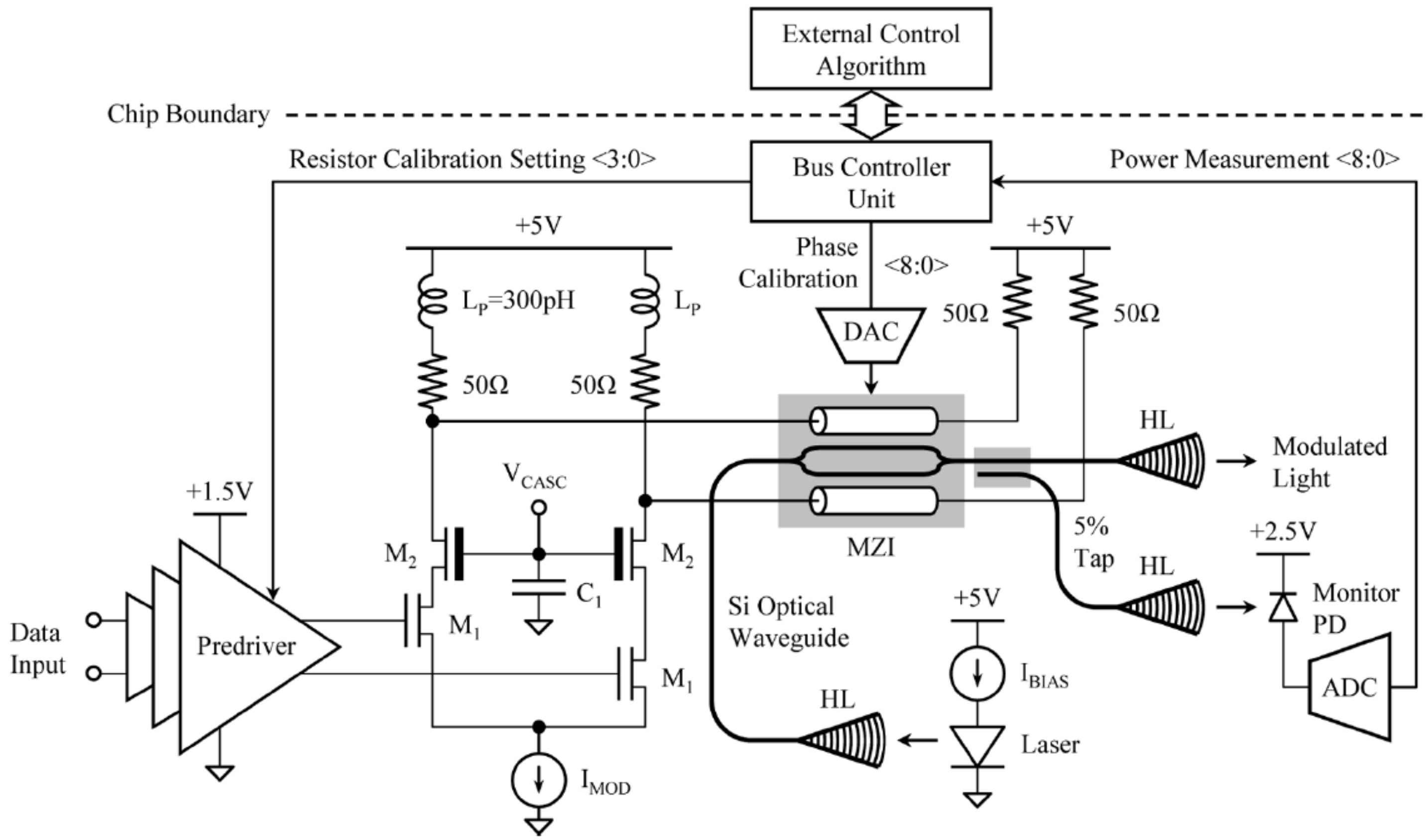
[Webster CSICS 2015]



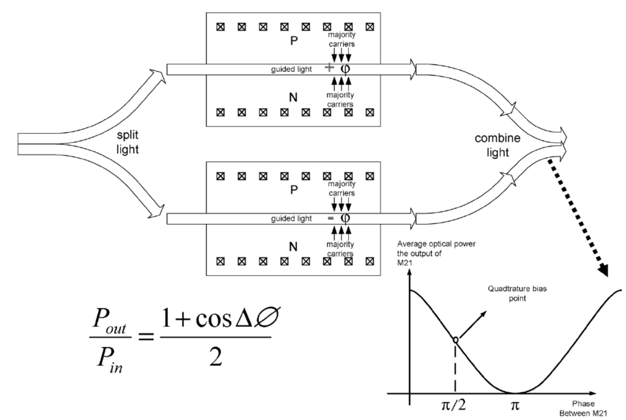
- With a MOS capacitor structure, a change in the accumulation carrier density occurs with the applied gate voltage
- The resultant change in the carrier density within the MOS capacitor region causes the refractive index to change
- Very large changes in charge density can be achieved!

Traveling-Wave MZM Driver

[Analui JSSC 2006]



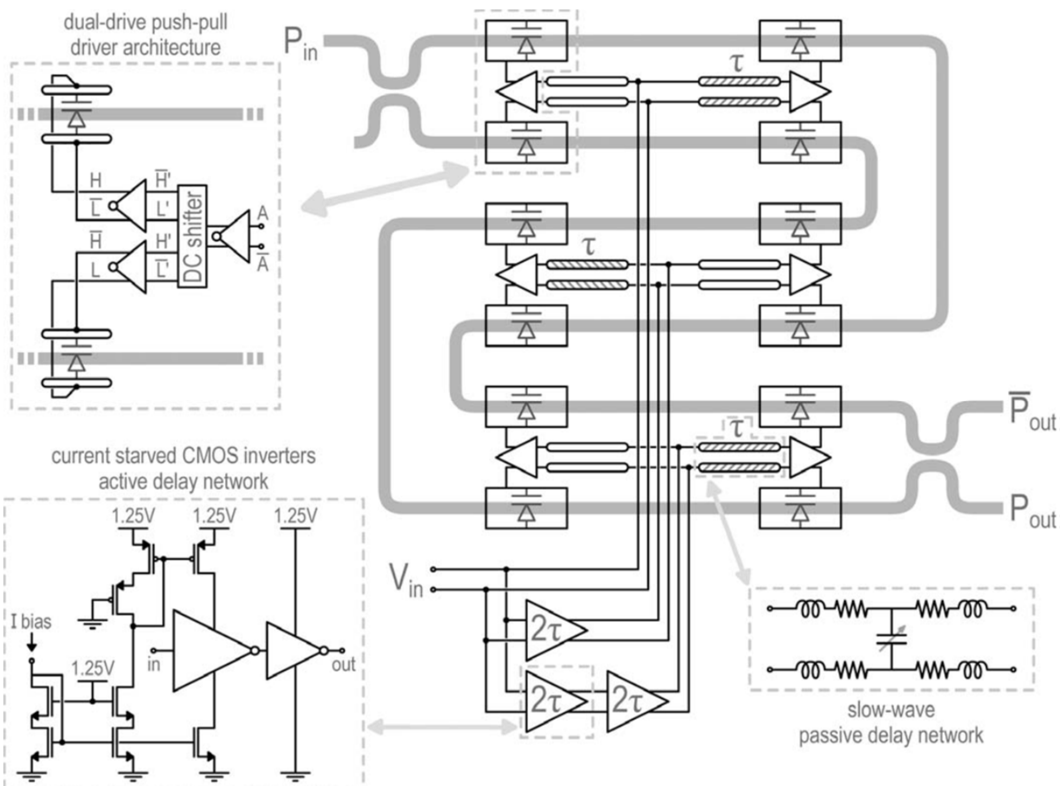
- Depletion-mode MZM is driven with a $5V_{ppd}$ signal

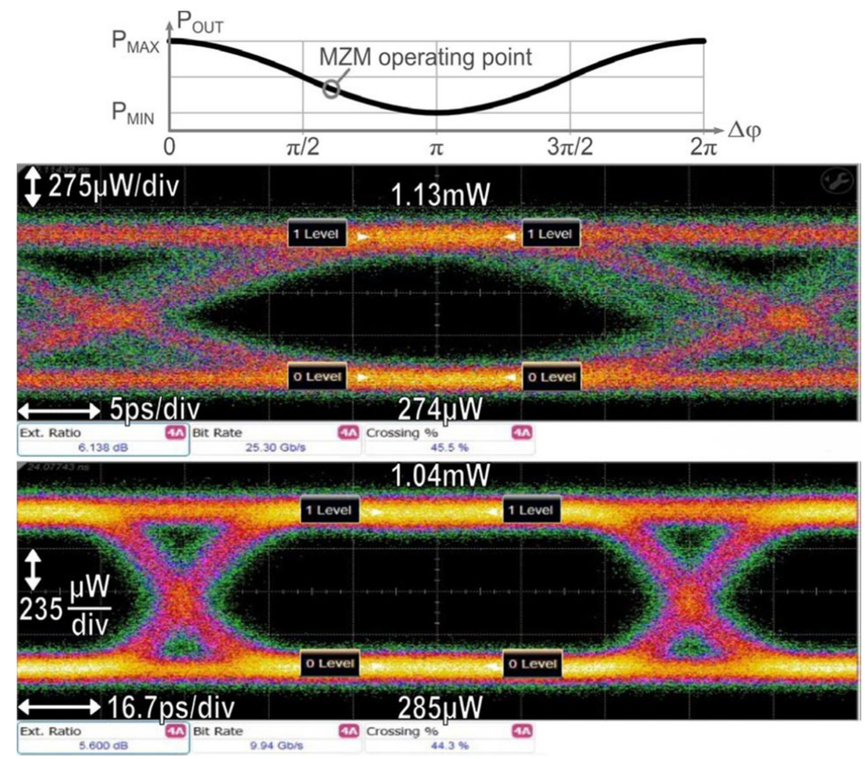


$$\frac{P_{out}}{P_{in}} = \frac{1+\cos\Delta\varnothing}{2}$$

Distributed MZM Driver

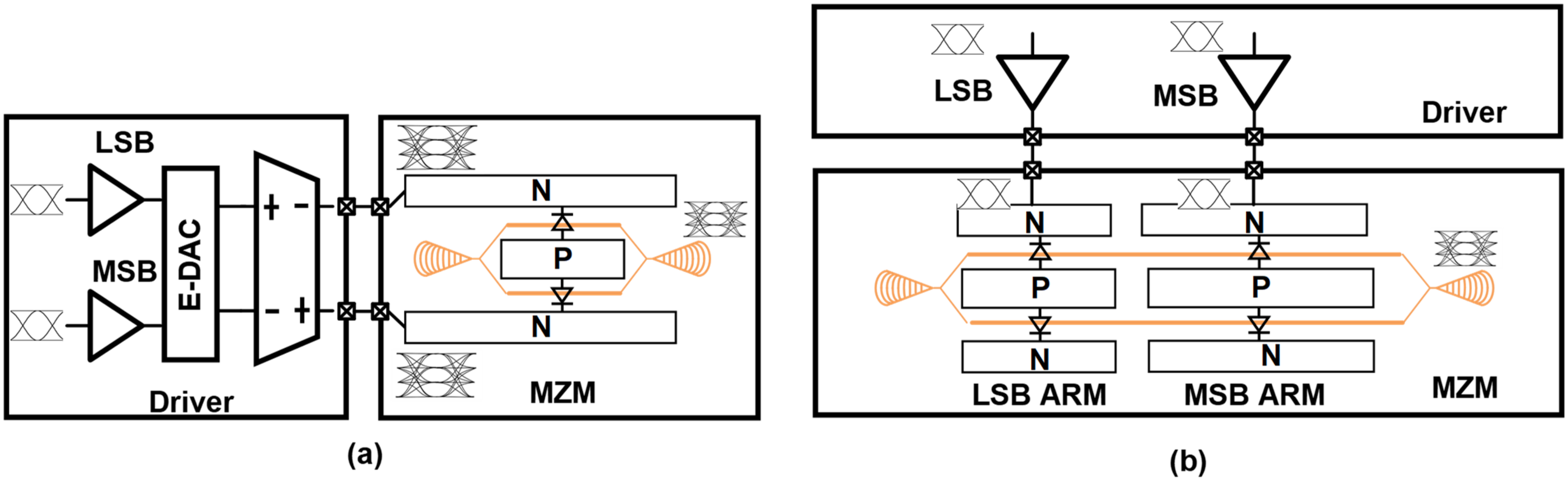
[Cignoli ISSCC 2015]





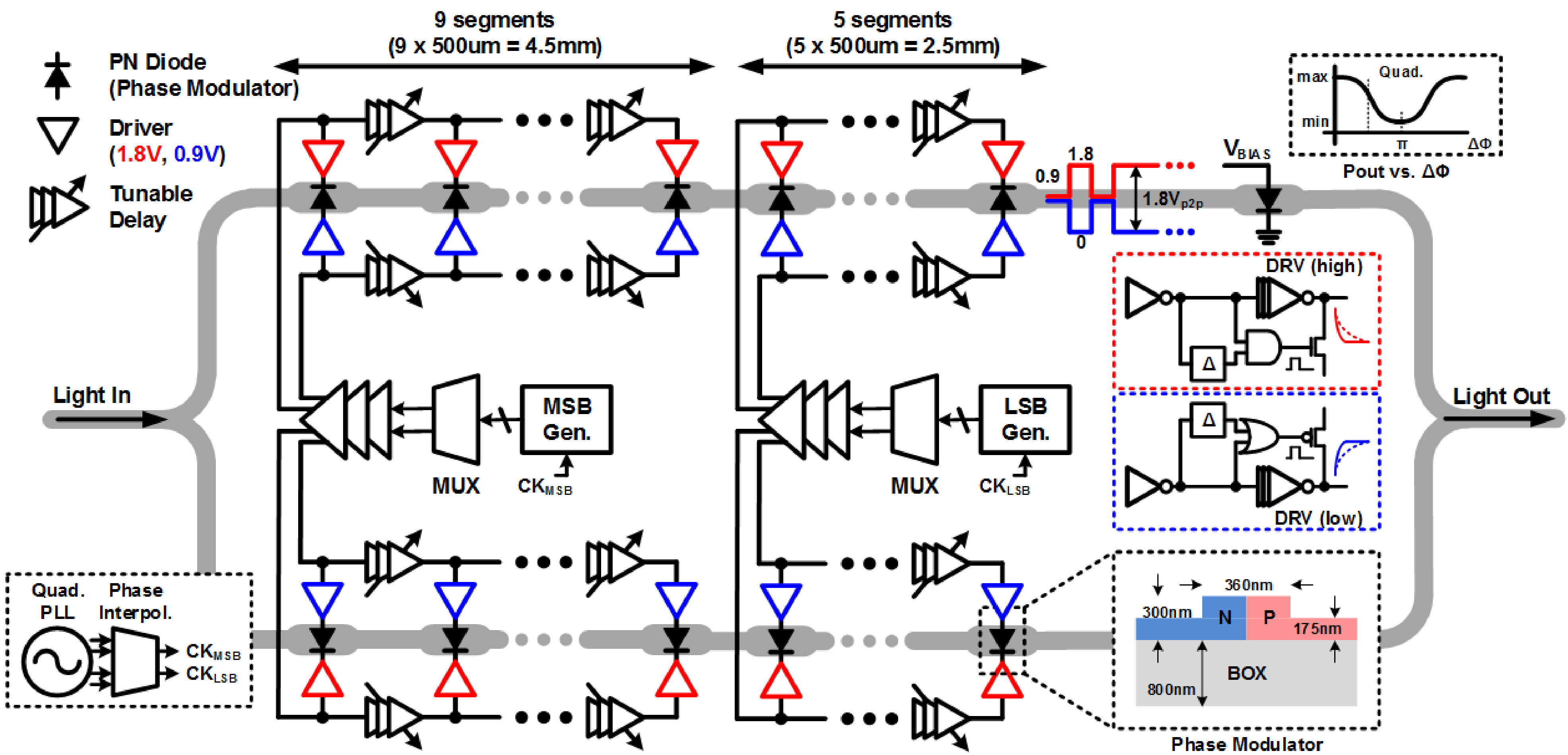
- Allows for CMOS style drivers
- Well suited for a monolithic silicon photonic process
- Hybrid integration requires may pad connections between CMOS/silicon photonic die

PAM4 Level Generation w/ MZMs



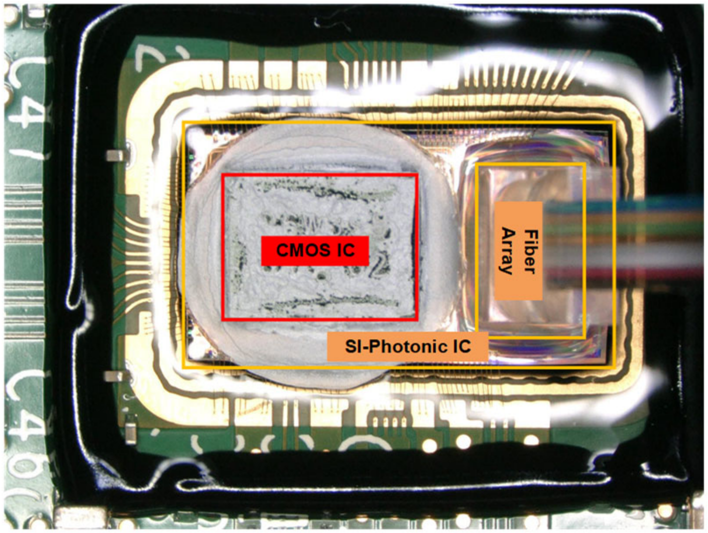
- E-DAC PAM4 TX
  - PAM4 driver bandwidth and swing limitation
  - Multi current/voltage level
- O-DAC PAM4 TX
  - Velocity mismatch between LSB and MSB
  - Multi driver design

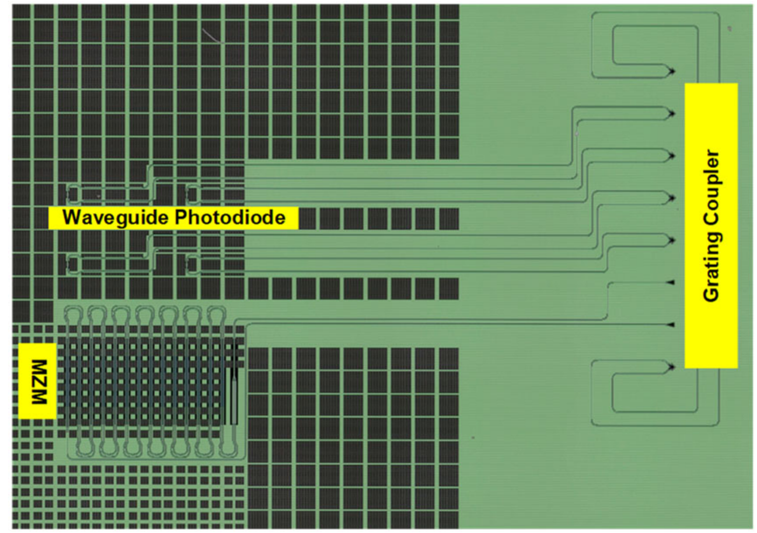
Optical DAC NRZ/PAM4 Reconfigurable MZM TX



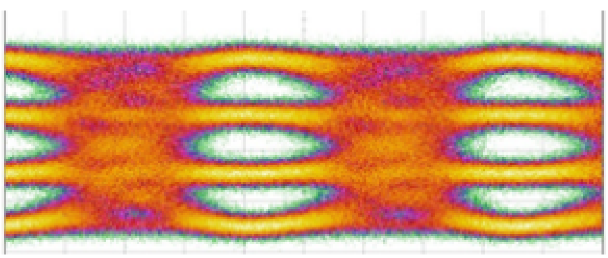
- 5 LSB segments and 9 MSB segments

56Gb/s PAM4 16nm FinFET CMOS Prototype

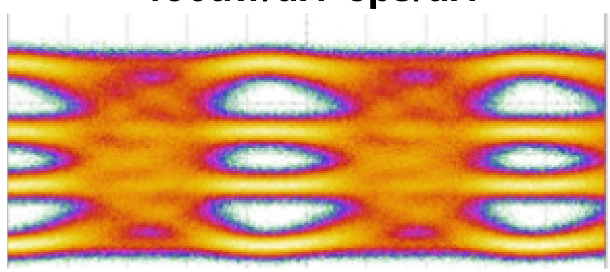




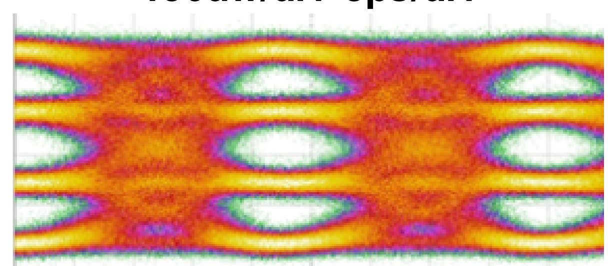
150uw/div 8ps/div



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

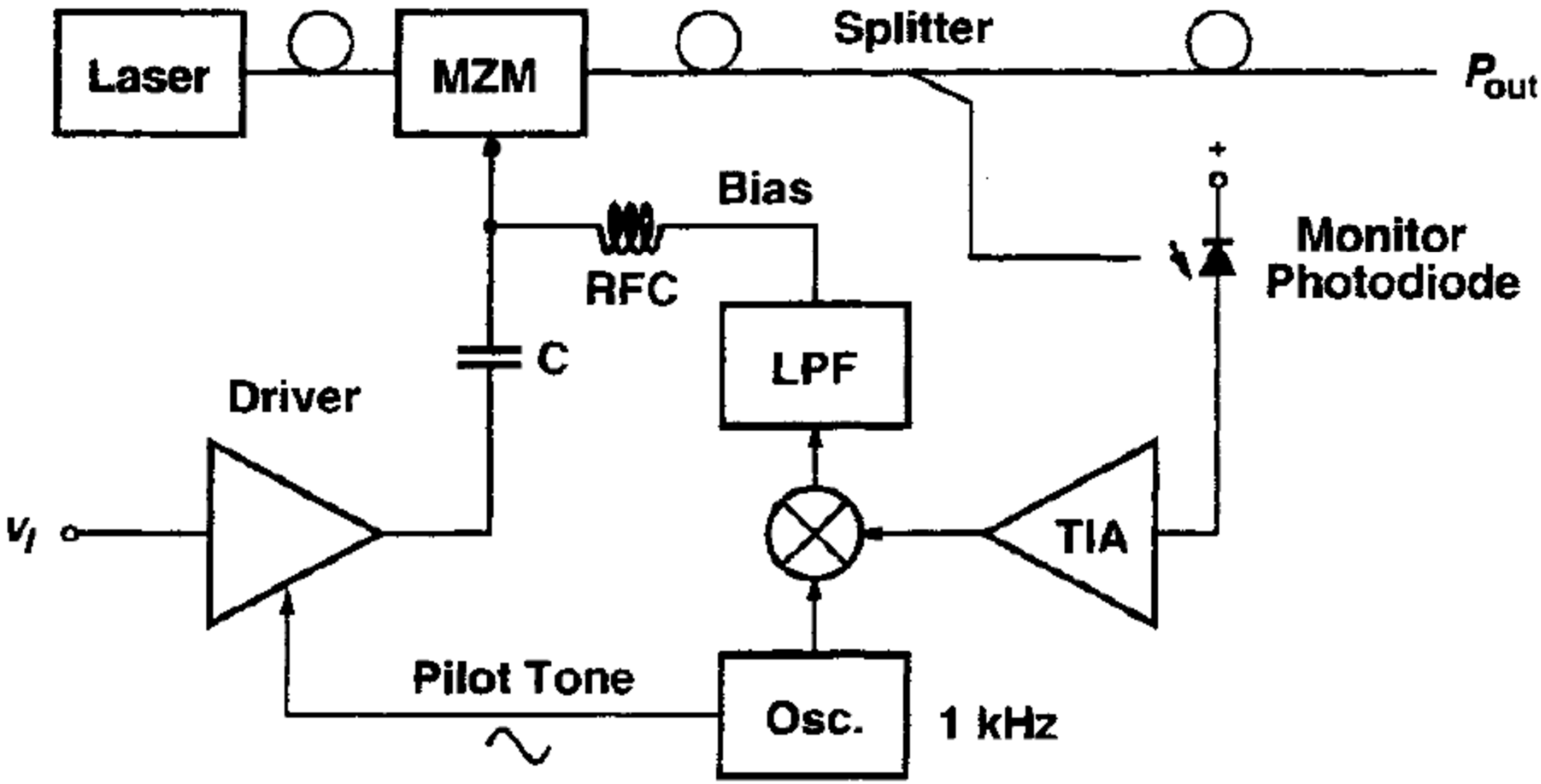
MZM Transmitter Performance Summary

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