Predictions of CMOS Compatible On–Chip Optical Interconnect

Guoqing Chen, Hui Chen, Mikhail Haurylau,
Nicholas Nelson, Philippe M. Fauchet,
and Eby G. Friedman

Department of Electrical and Computer Engineering
University of Rochester

David H. Albonesi

Computer Systems Laboratory
Cornell University

NSF CCR-0304574

April 2, 2005 SLIP Conference

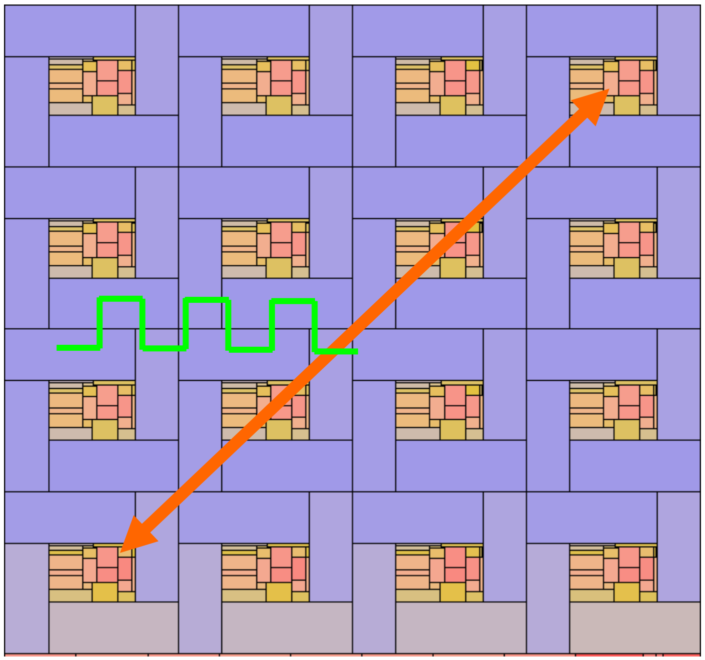
Agenda

- Introduction
- On-chip CMOS optical data paths
- Optical interconnect vs. electrical interconnect
- Conclusions

Agenda

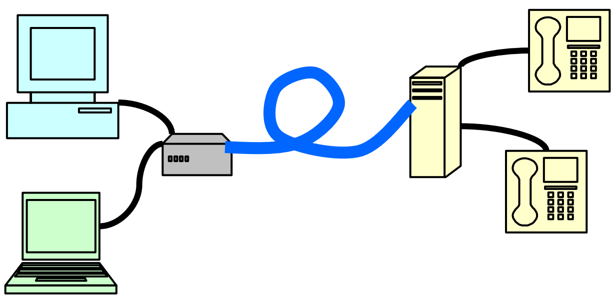
- Introduction
- On-chip CMOS optical data paths
- Optical interconnect vs. electrical interconnect
- Conclusions

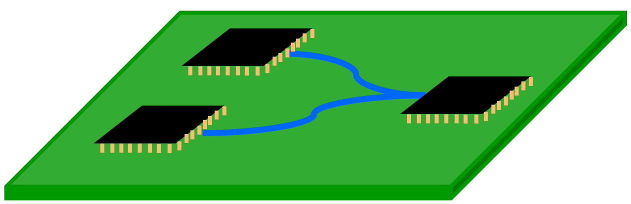
Interconnect Centric Design

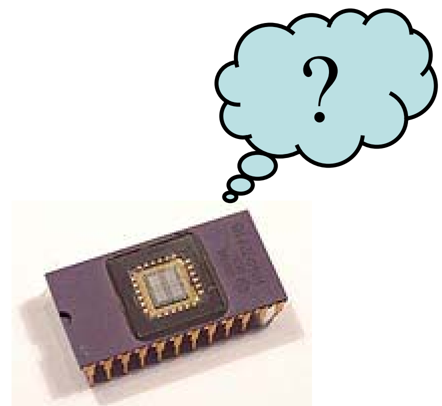


- Multiple design criteria should be considered in the interconnect design process

Optical Interconnect

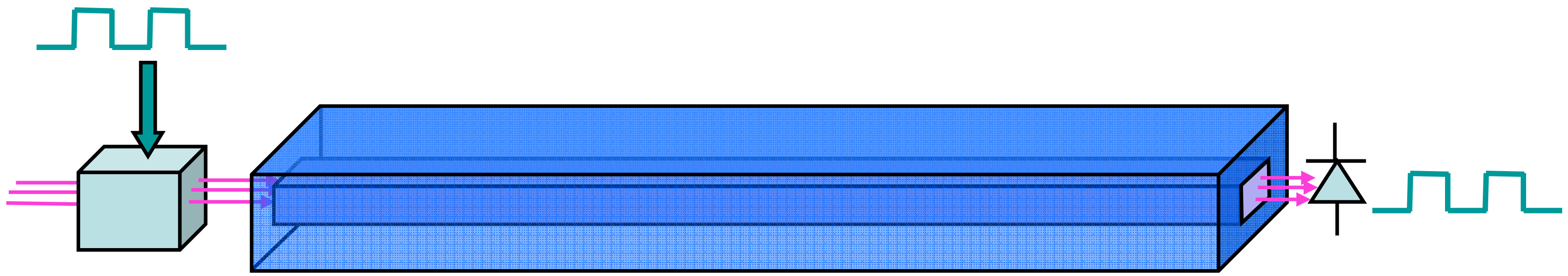




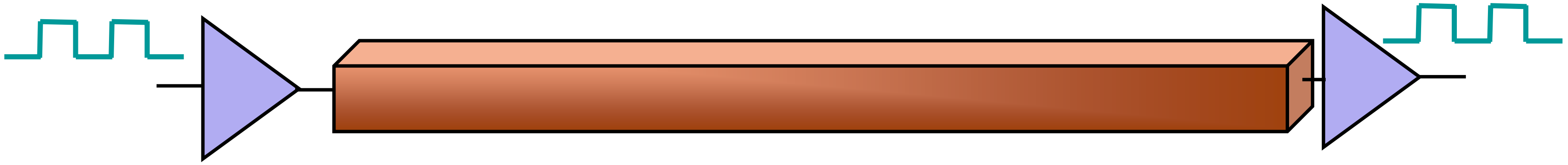


- Cost-effective
- CMOS-compatible
- High speed
- Compact

On-Chip Optical Interconnect



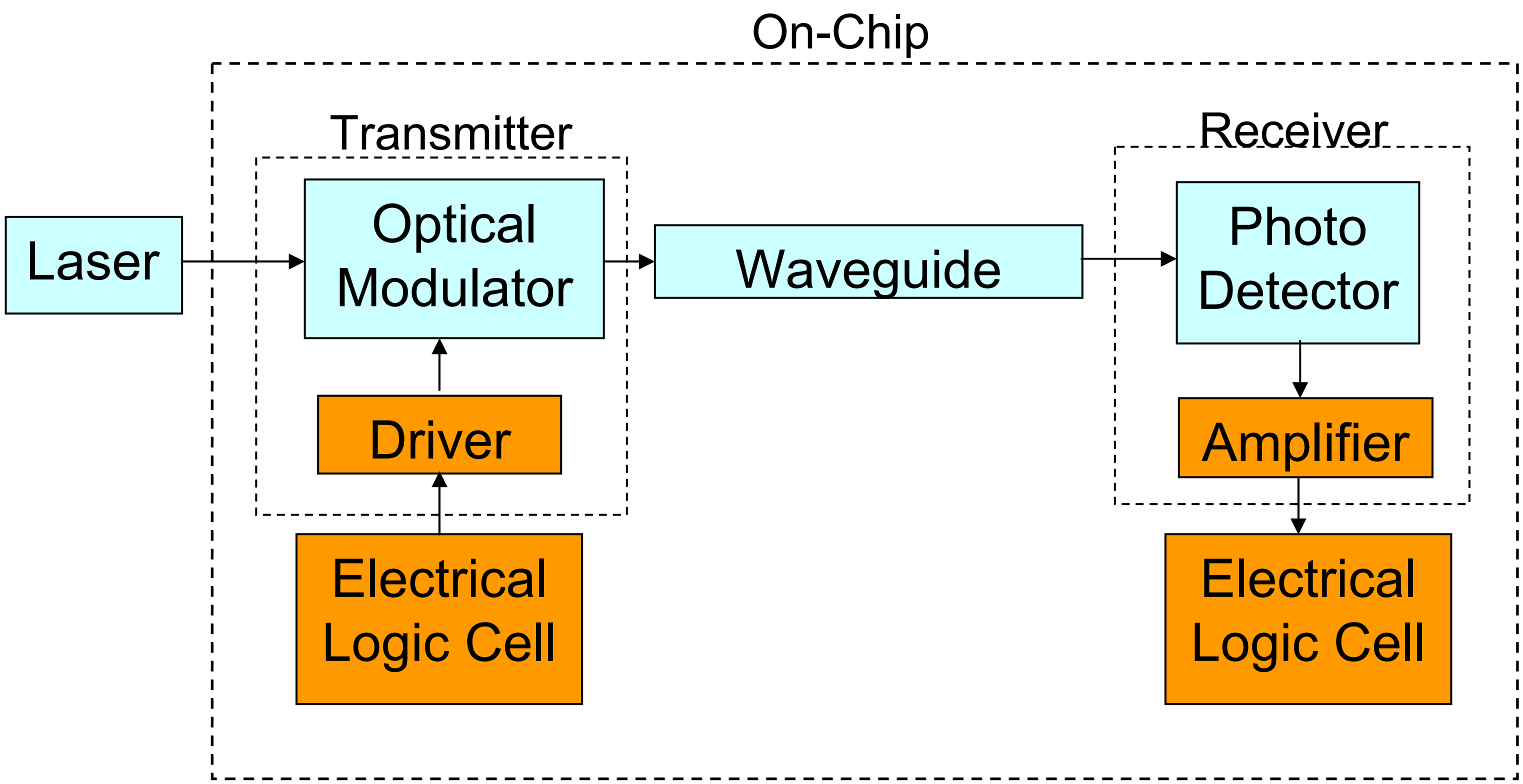
When and in what situation is optical interconnect better than electrical interconnect?



Agenda

- Introduction
- On-chip CMOS optical data path
- Optical interconnect vs. electrical interconnect
- Conclusions

On–Chip Optical Interconnect Data Path



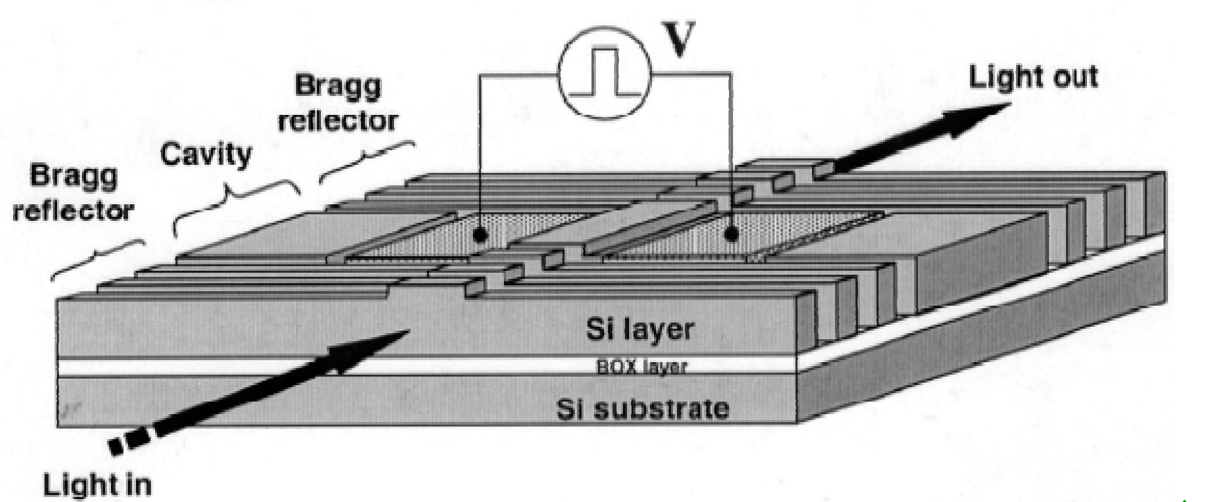
Modulators – Choice of Structures

Electrical Structure

Optical Structure

	p-i-n diode	MOS capacitor
Mach-Zehnder		
Microresonator		

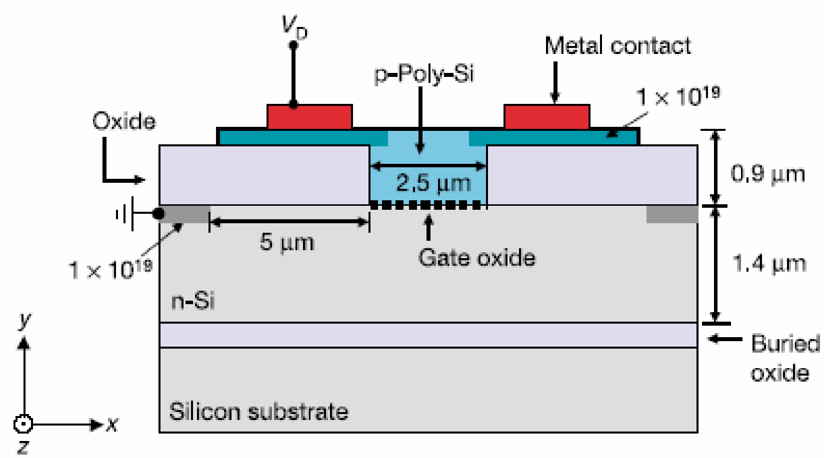
P-i-n Diode : Microresonator

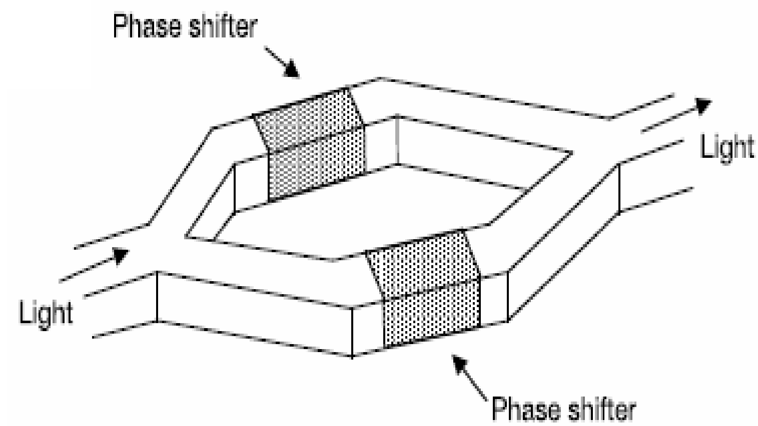


- Size (20 µm) ↑
- Power consumption (mWs) ↑
- CMOS compatible ↑
- Speed (injection-based) ✕

C. A. Barrios, V. R. Almeida, and M. Lipson, "Low Power-Consumption Short-Length and High-Modulation-Depth Silicon Electrooptic Modulator," J. of Lightwave Tech., Vol. 21, No. 4, pp. 1089-1098, April 2003.

MOS Capacitor : Mach-Zehnder

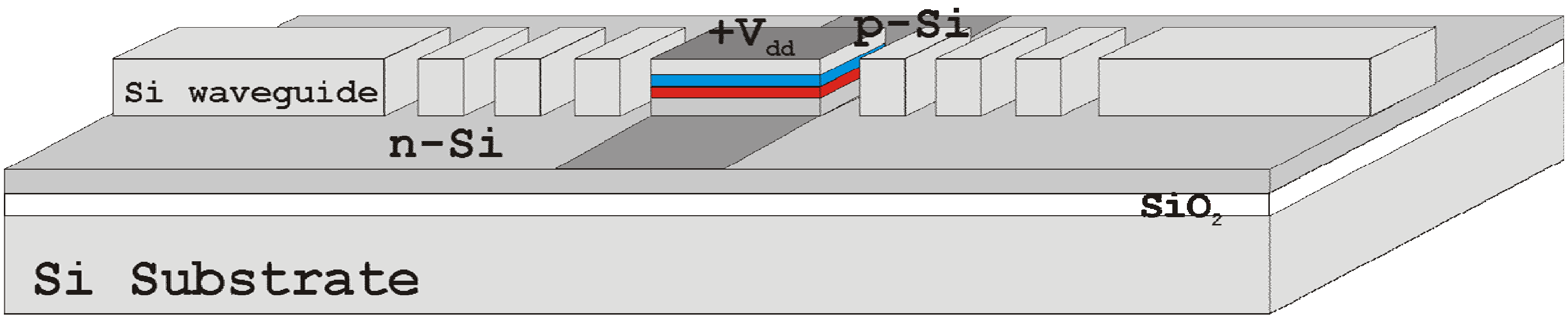




- Speed (1 GHz and up)
- CMOS compatible
- Size (10 mm)
- Power consumption (watts)

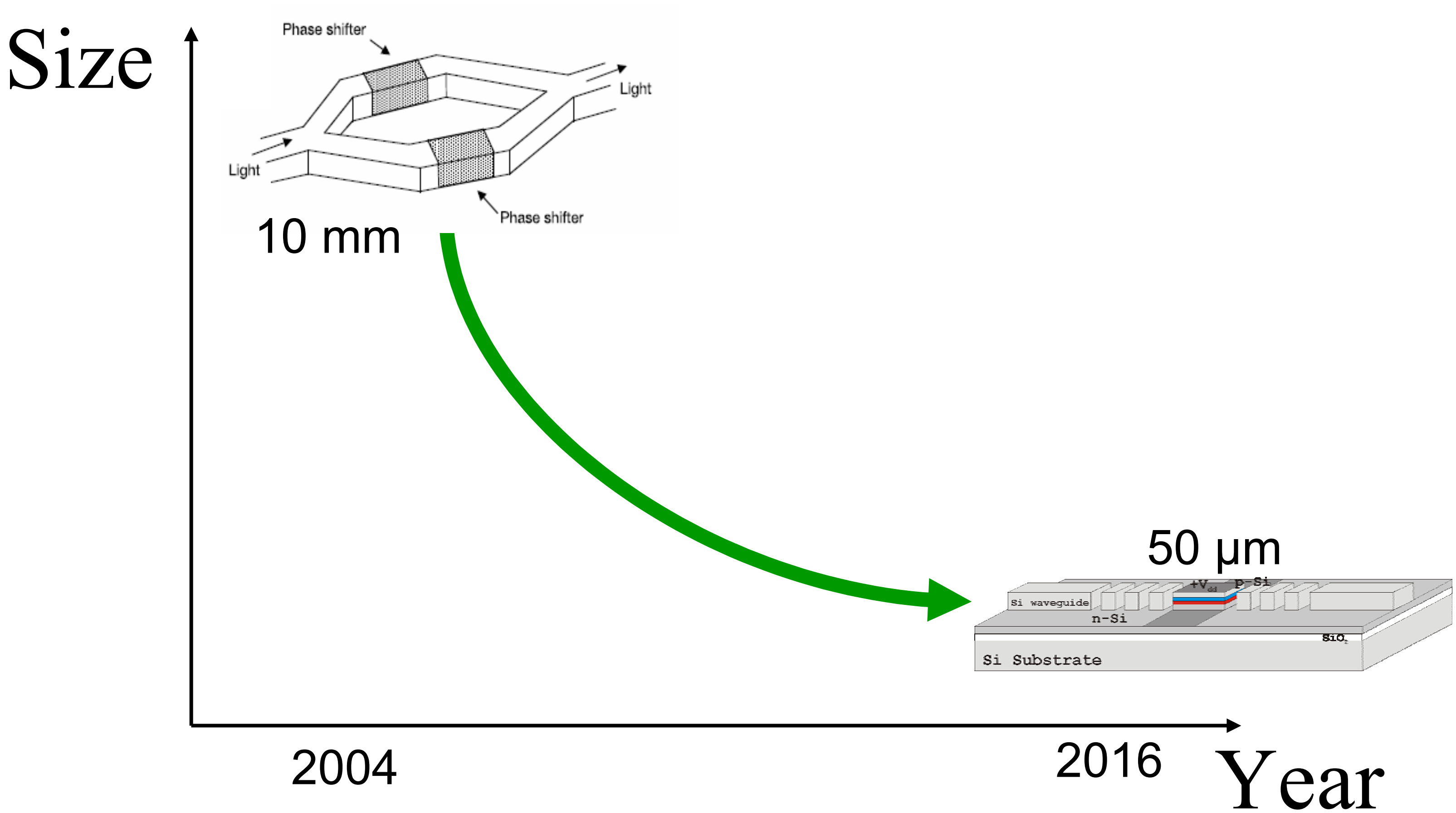
* A. Liu *et al*, "A High-Speed Silicon Optical Modulator Based on Metal-Oxide-Semiconductor Capacitor," *Nature*, Vol. 427, pp. 615-618, February 2004.

Proposed Modulator Model



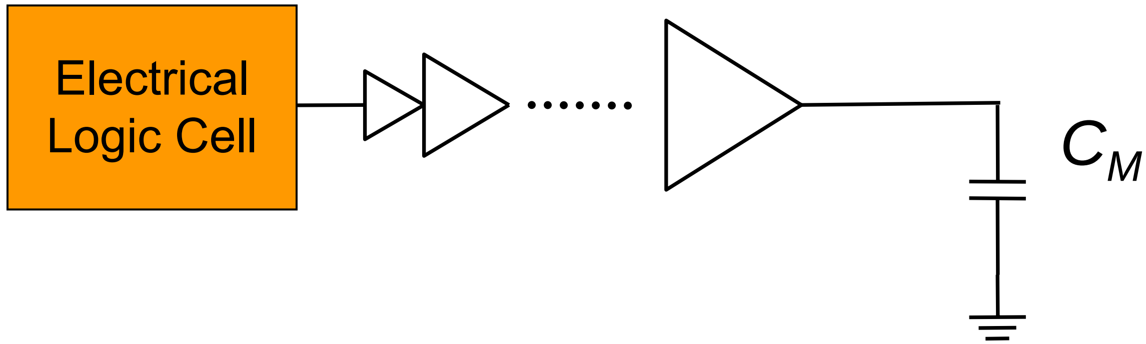
- High speed ↑
- CMOS compatible ↑
- Compact size ↑
- Low power ↑

Projection of Modulator Size



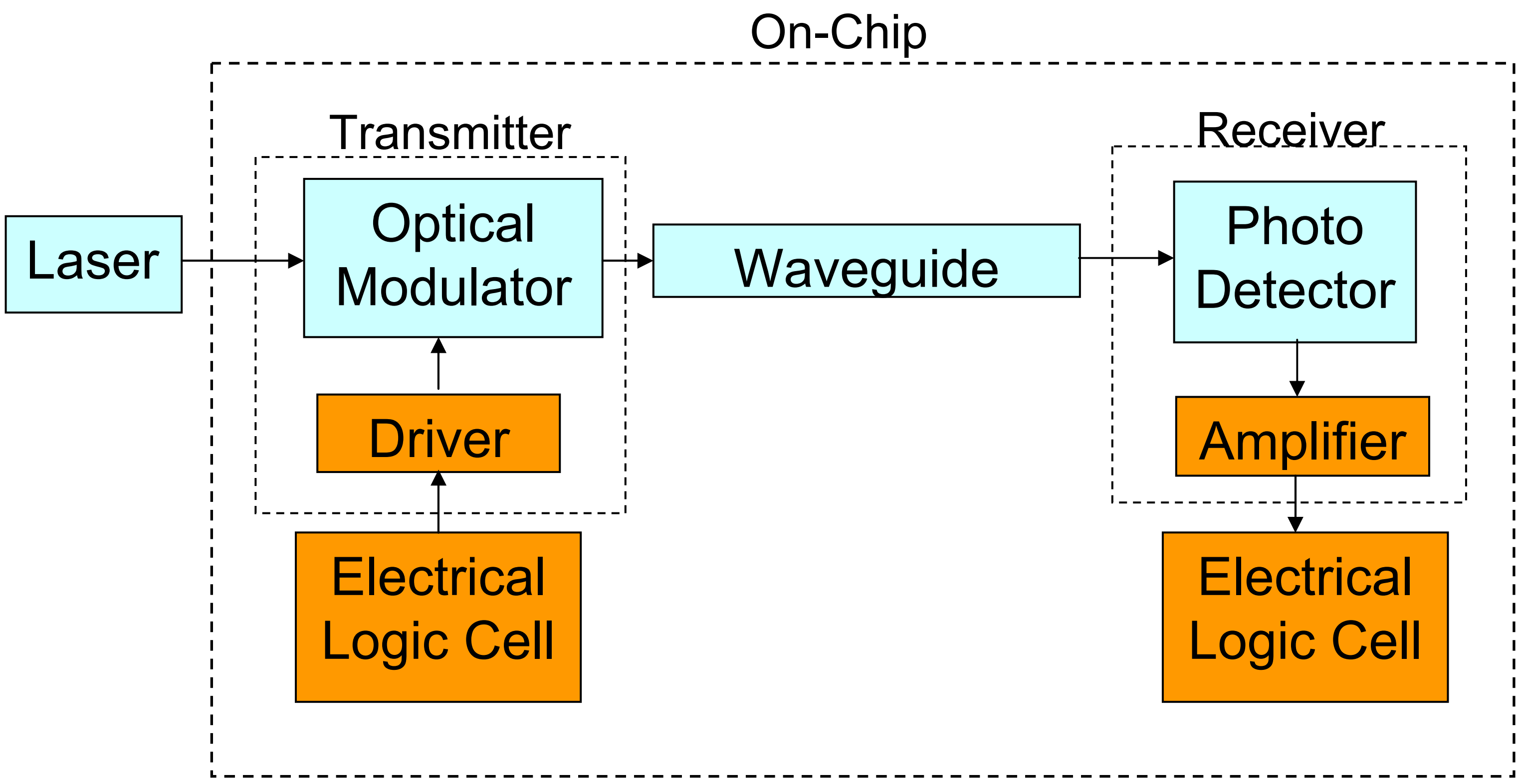
A. Liu *et al*, "A High-Speed Silicon Optical Modulator Based on Metal-Oxide-Semiconductor Capacitor," *Nature*, Vol. 427, pp. 615-618, February 2004.

Model of Modulator Driver

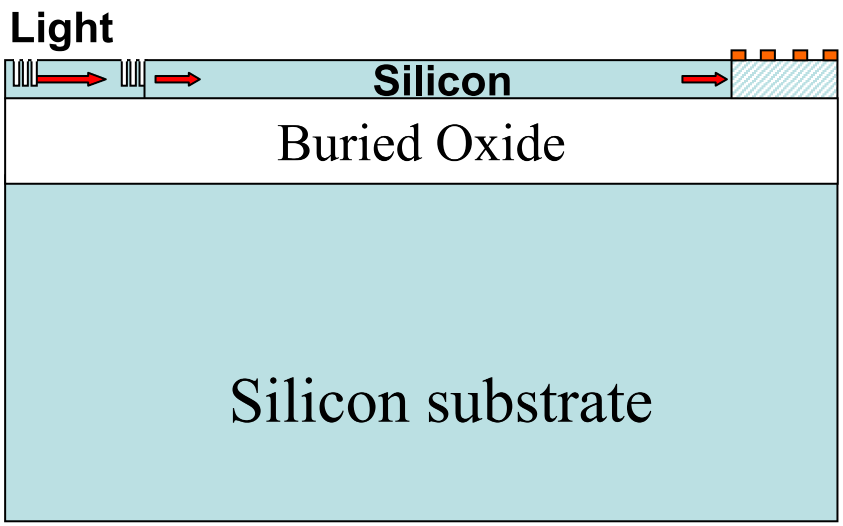


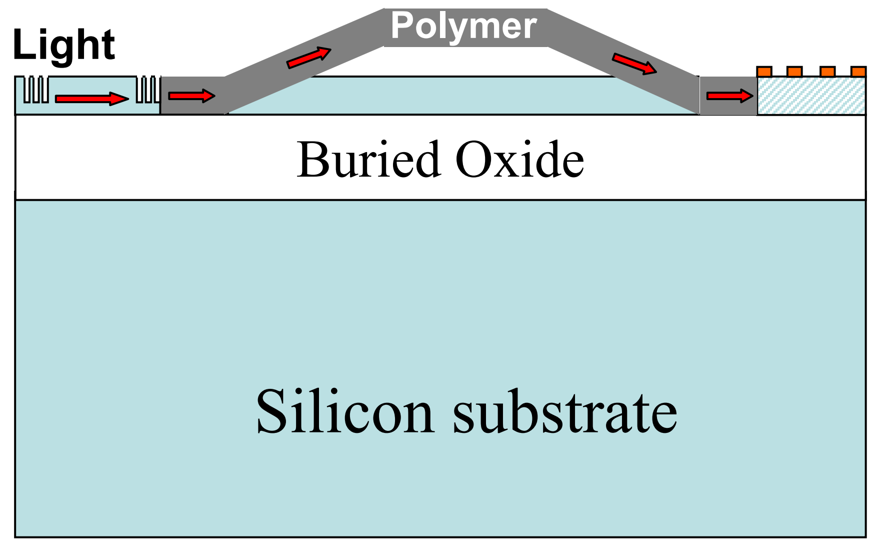
- Optical modulator is modeled as a lumped capacitor
- A series of tapered buffers used to drive C_M
- The size of the buffers is optimized for minimum delay

On–Chip Optical Interconnect Data Path



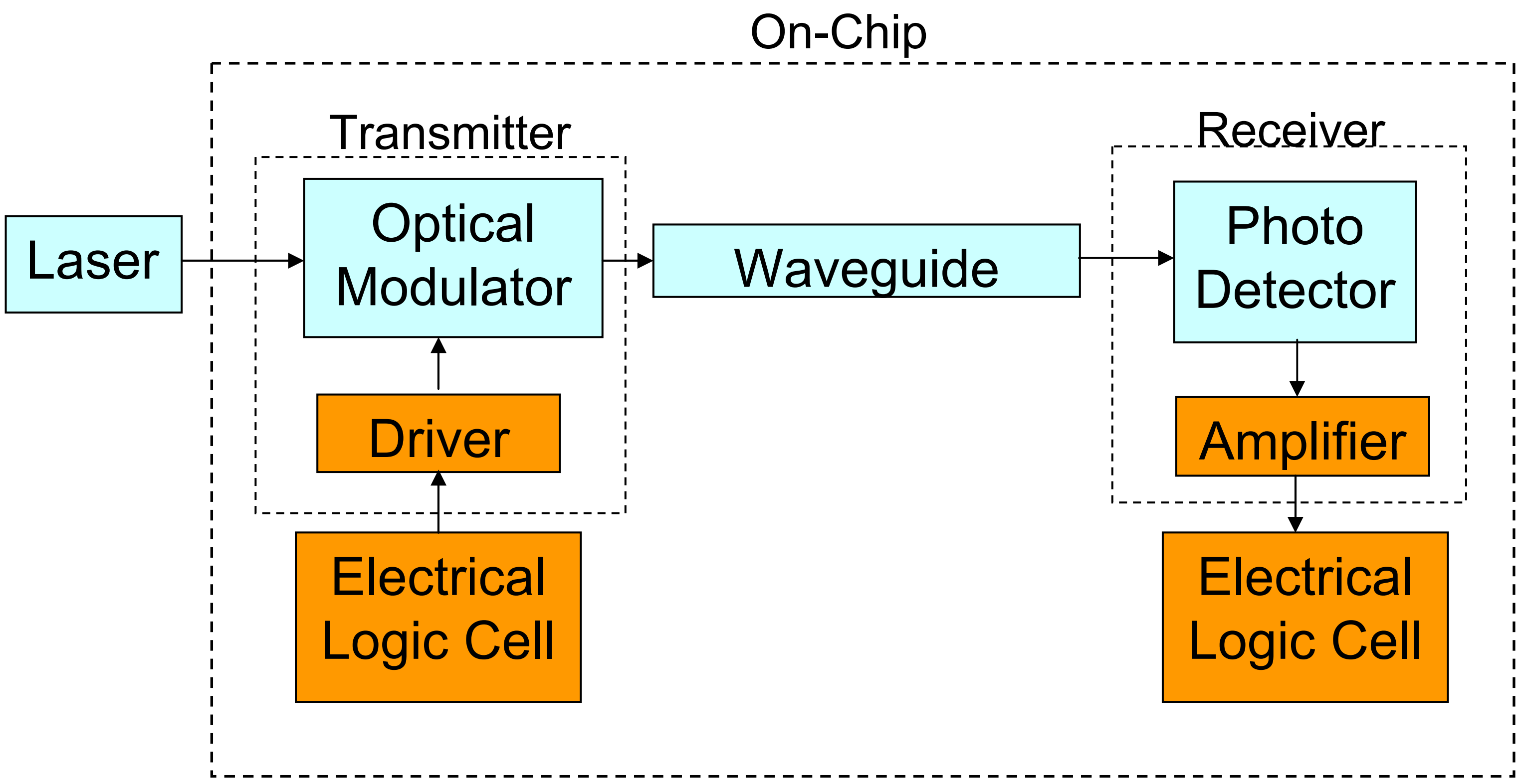
Waveguide



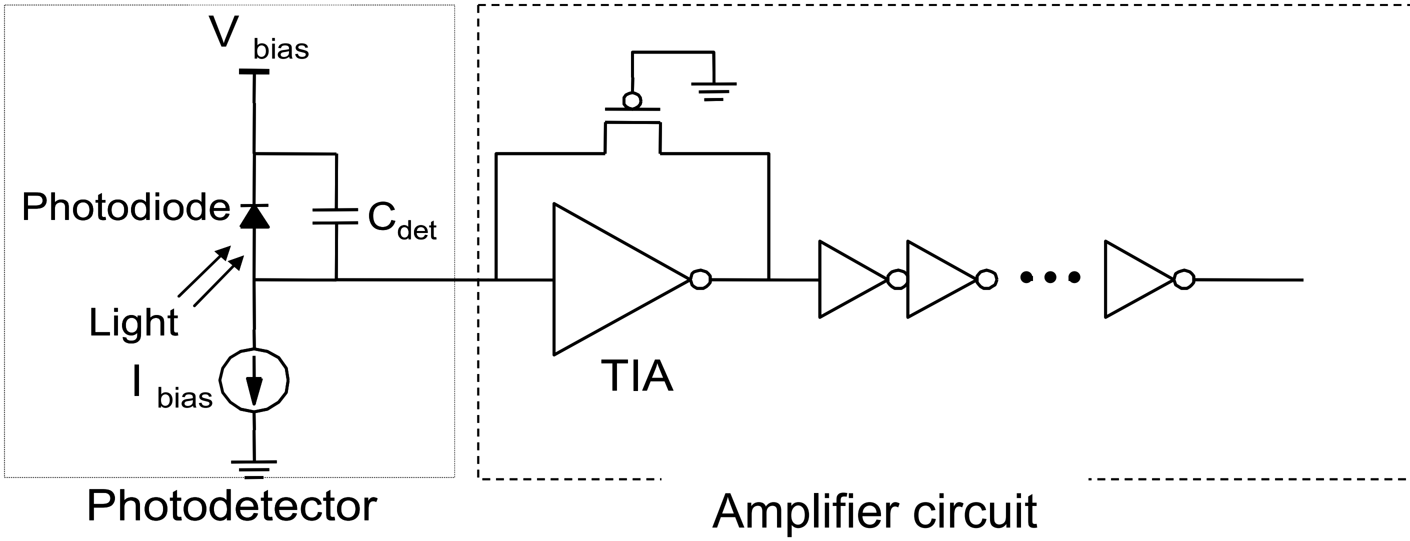


- Si waveguide
  - Consumes Si resources
  - High refractive index ~ 3.5
    - Narrower waveguide
    - Slower light speed
- Polymer waveguide
  - Additional layer
  - Low refractive index ~ 1.4
    - Wider waveguide
    - Faster light speed

On–Chip Optical Interconnect Data Path



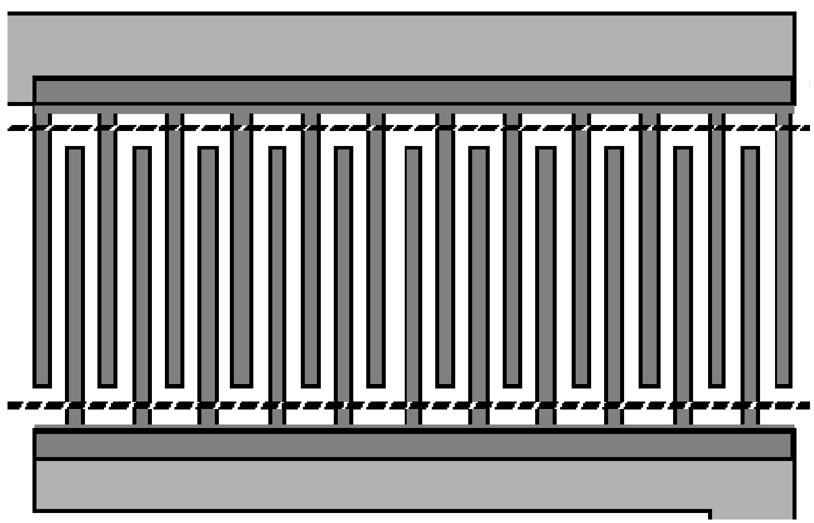
Model of Optical Receiver



- Optical receiver is composed of a photodector and an amplifier circuit

Photodetector

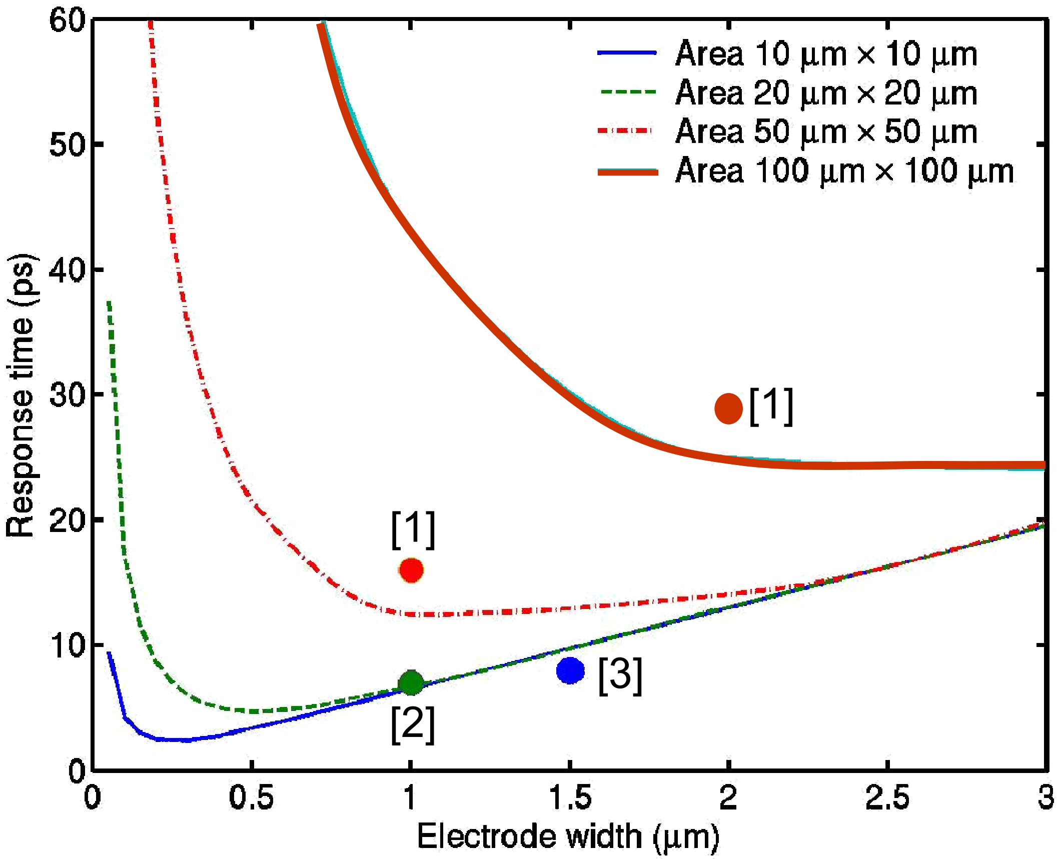
- Material: Ge or SiGe
  - Longer wavelength absorption window
    - Compatible with CMOS
- Structure: Metal-semiconductor-metal (MSM)
  - High speed
  - Easy to fabricate
  - Reasonable quantum efficiency



Photodetector Optimization

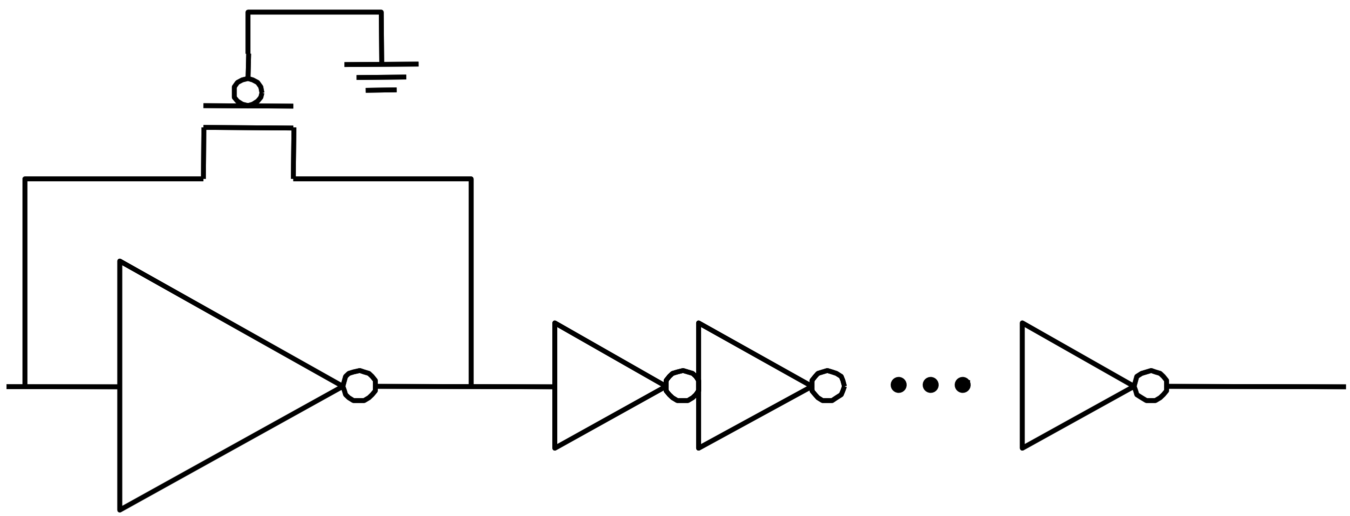
- Response time
  - $T_r = \sqrt{\tau_{tr}^2 + \tau_{RC}^2}$
  - Transit time
  - *RC* response time
- Expected size
  - In ten years

    5 μm x 5 μm
  - Limited by the optical mode size



[1] S.V.Averine *et al, Solid-State Electronics*, Vol. 45, No.3, pp. 441-446, March 2001.
[2] S.Y.Chou *et al*, *Applied Physics letter*, Vol. 61, No. 15, pp. 1760-1762, October, 1992.
[3] D. Buca *et al*, *Journal of Applied Physics,* Vol. 92, No. 12, pp. 7599-7605, December 2002.

Amplifier Circuit



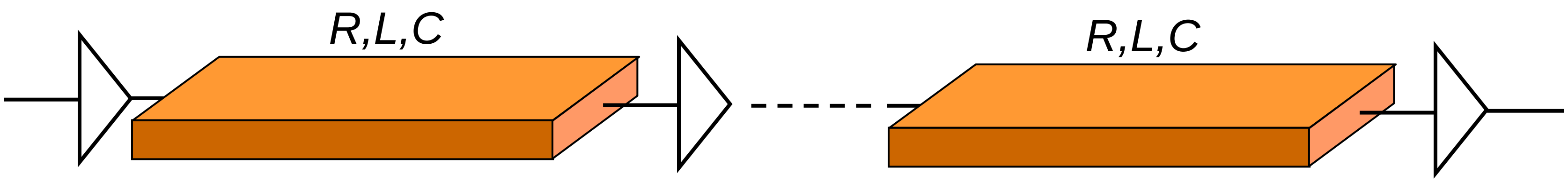
- Amplifier is designed to satisfy noise and bandwidth requirements *
  - BER: 10^{-15}
  - 3 dB bandwidth: 0.7 x bit rate (NRZ)

P. Kapur, *Scaling Induced Performance Challenges/Limitations of On-Chip Metal Interconnects and Comparisons with Optical Interconnects*, Ph. D. Thesis, Stanford University, Stanford, California, 2002

Agenda

- Introduction
- On-chip CMOS optical data path
- Optical interconnect vs. electrical interconnect
- Conclusions

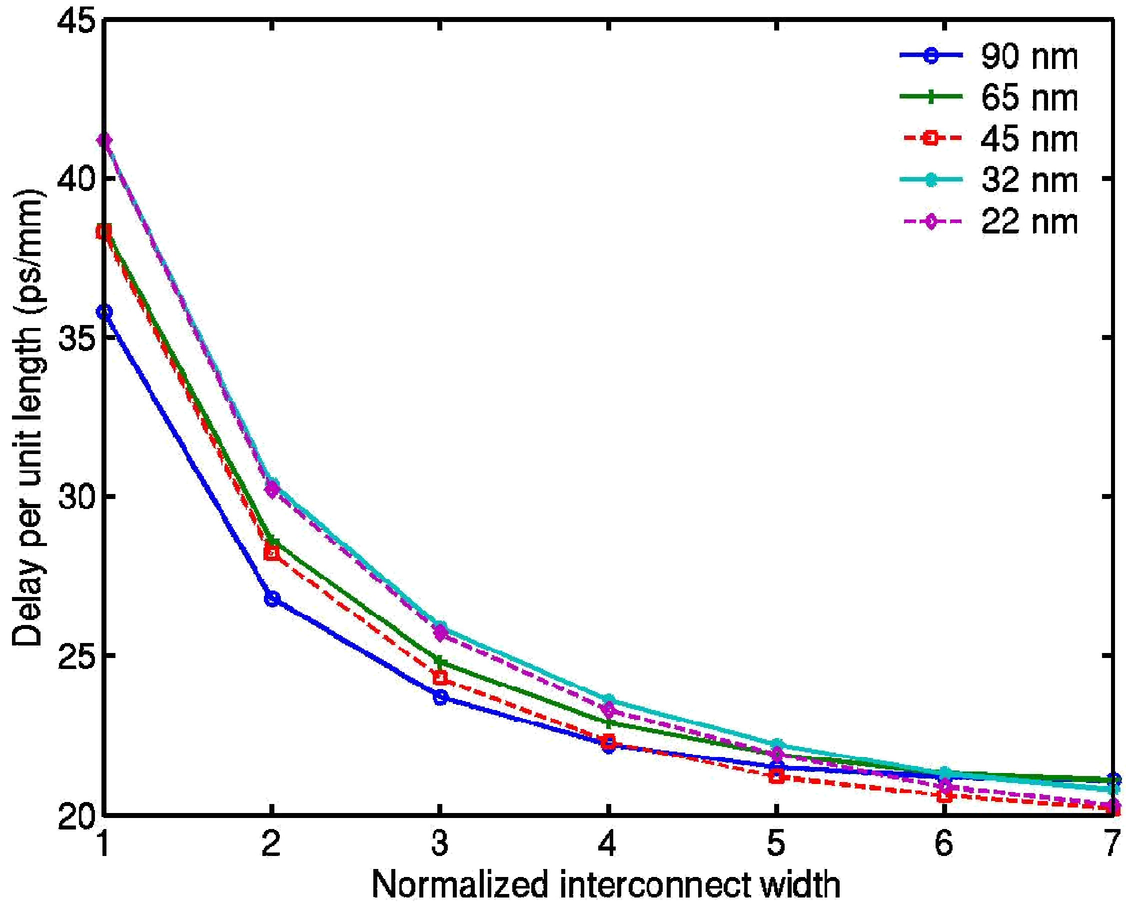
Electrical Interconnects with Repeaters



- Electrical interconnects are modeled as *RLC* transmission lines
- Three dimensions of freedom
  - Interconnect width
  - Number of repeaters
  - Size of repeaters

Minimum Delay of Electrical Interconnect

- Scaling has a small effect on the delay of global interconnect with repeaters
  - The minimum achievable delay is constant for advanced technology nodes: 20 ps/mm



L = 0.5 pH/μm
Line spacing = W_{min}

Delay of Optical Interconnect

Year	2004	2007	2010	2013	2016
Technology node	90 nm	65 nm	45 nm	32 nm	22 nm

Modulator driver	83.7	45.8	25.8	16.3	9.5
Modulator	114.0	52.1	30.4	20.0	14.3
Waveguide	46.7	46.7	46.7	46.7	46.7
Photo-detector	1.4	0.5	0.3	0.3	0.2
Receiver amplifier	37.5	16.9	10.4	6.9	4.0

Total optical	283.3	162.0	113.6	90.2	74.7

Unit: ps, Length = 10 mm

- Electrical interconnect delay: 20 ps/mm

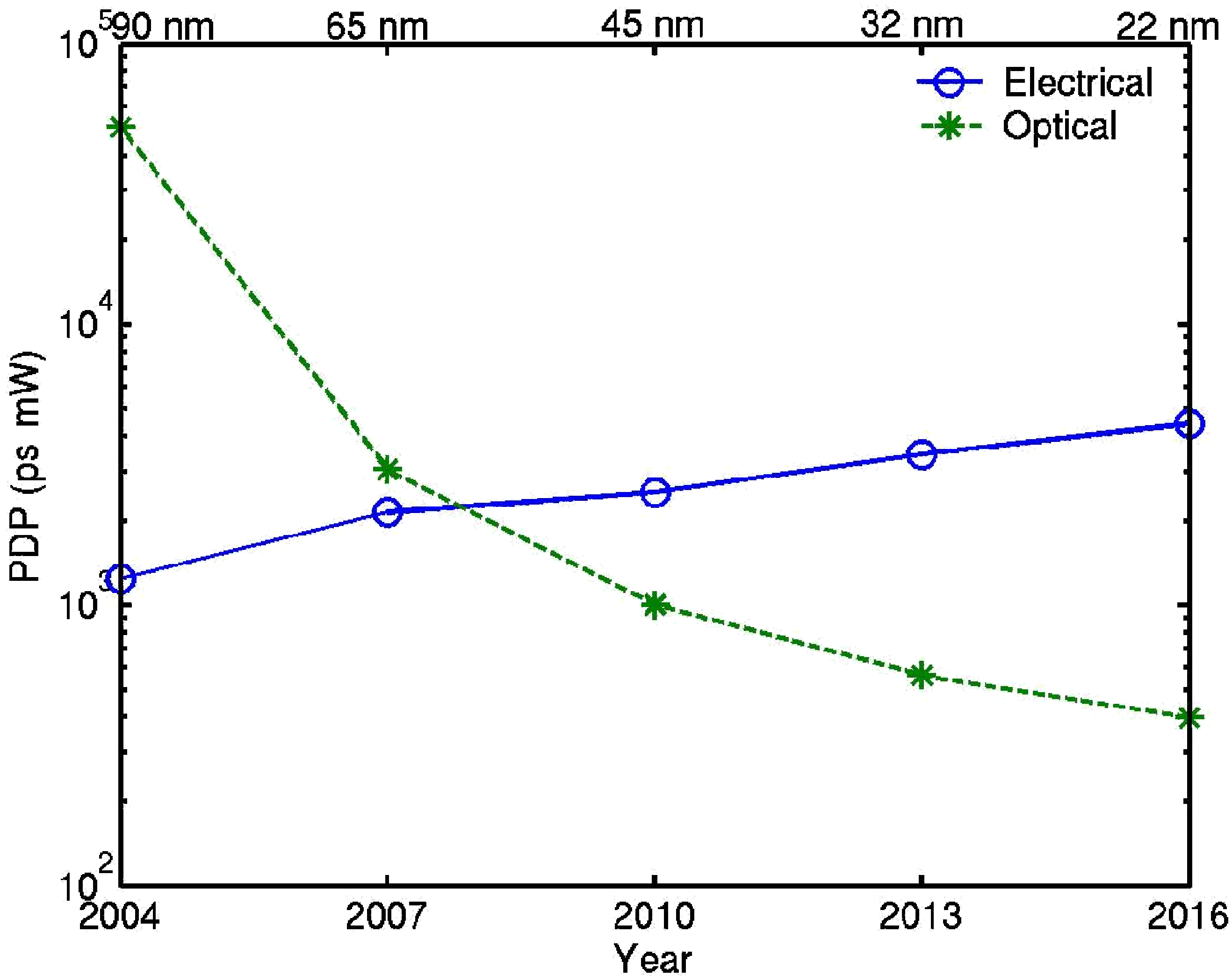
Power Consumption in Optical Interconnect

- Assumptions
  - Input optical power ~ 0.2 mW
  - Power consumption in the optical interconnect is independent of interconnect length
    - Optical power loss in waveguide is ignored

Year	2004	2007	2010	2013	2016
Technology node	90 nm	65 nm	45 nm	32 nm	22 nm
Transmitter	177.5	18.4	8.6	6.0	5.0
Receiver	0.4	0.3	0.2	0.3	0.3
Total	177.9	18.7	8.8	6.3	5.3

Unit: mW

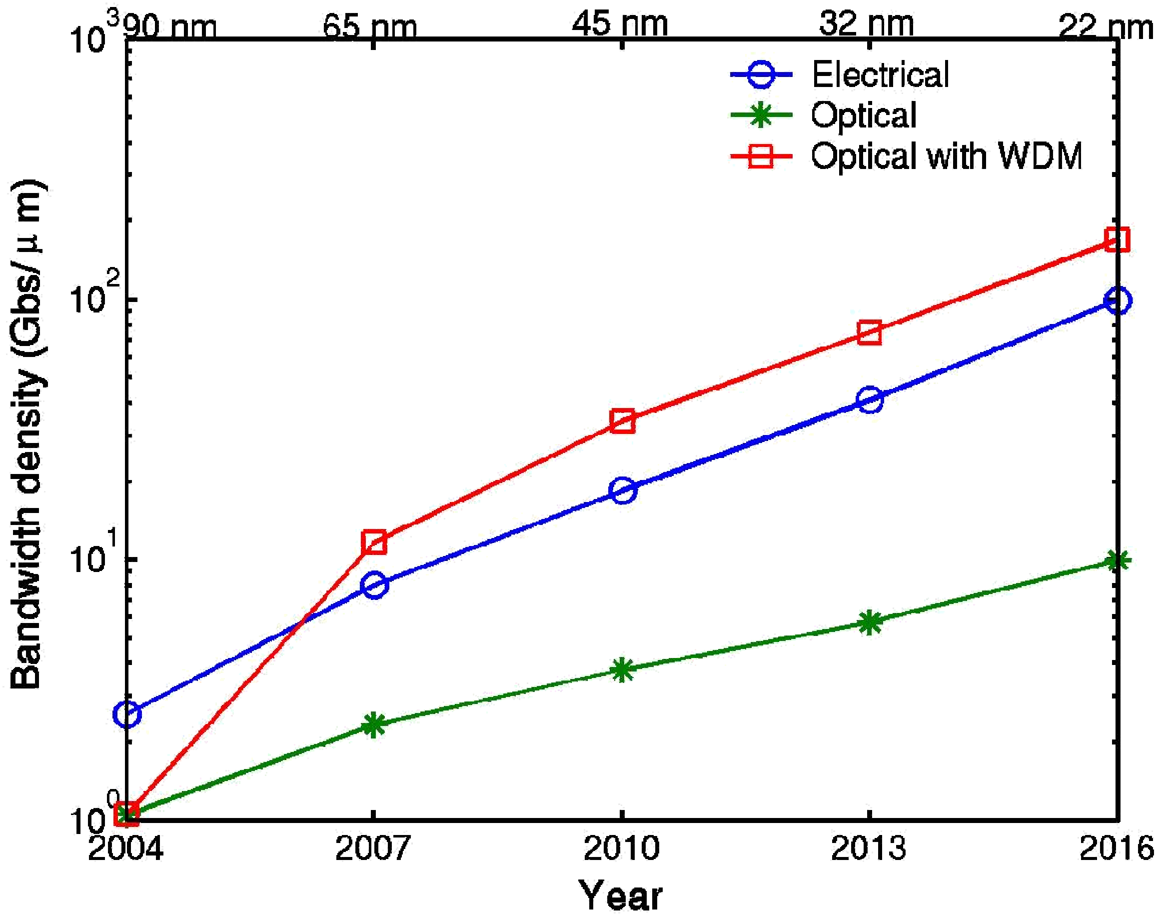
Power-Delay Product (PDP)



Length = 10 mm

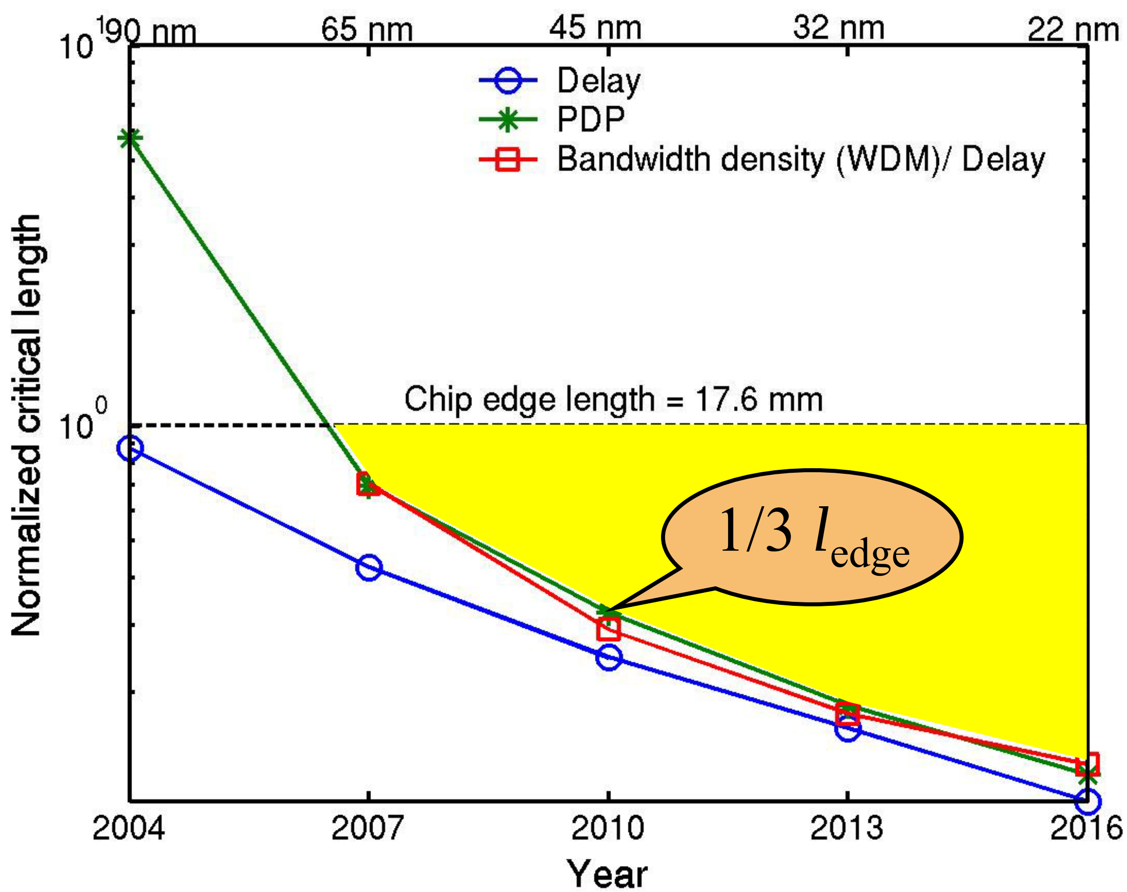
Bandwidth Density

- Bandwidth density
  - The ability to transmit data through a unit width
- The maximum bit rate is the clock rate
- Wavelength division multiplexing (WDM)
  - Four additional channels for each new technology node



Critical Length

- Critical length
  - The length beyond which optical interconnect is advantageous over electrical interconnect



Agenda

- Introduction
- CMOS compatible on-chip optical data path
- Performance prediction of optical interconnect compared with copper interconnect
- Conclusions

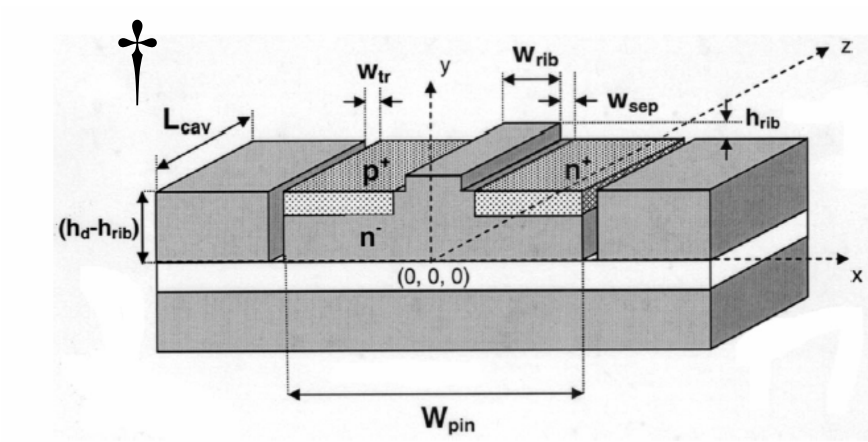
Conclusions

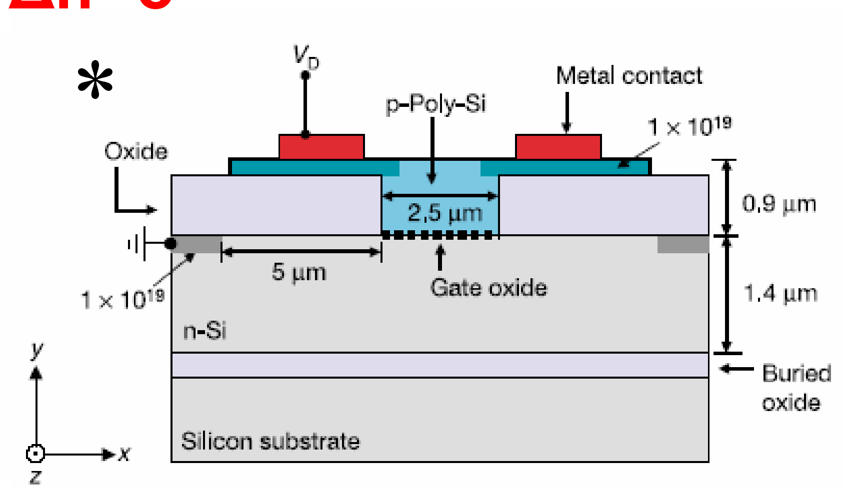
- Predictions of CMOS compatible on-chip optical interconnect are presented
  - Device models are described
  - Delay, power, and bandwidth are analyzed
- Modulator is the key component in an on-chip electro-optical system
- WDM is necessary for improving the bandwidth density of the optical interconnect
- The critical length is about 1/3 of the chip edge length at the 45 nm technology node

Backup

Electrical Structures

$$\Delta n_{eff} = \Delta n * \sigma$$





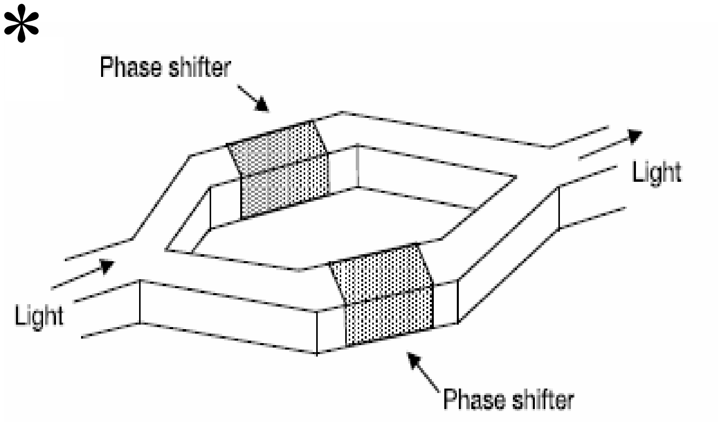
- P-i-n diode
  - Uniform injection over large areas, high Δn_{eff}
  - Slow (20 ps and higher)
- MOS capacitor
  - Carrier concentration varies in small area.
  - Very fast

* A. Liu *et al*, "A High-Speed Silicon Optical Modulator Based on Metal-Oxide-Semiconductor Capacitor", *Nature*, Vol. 427, pp. 615-618, February, 2004.

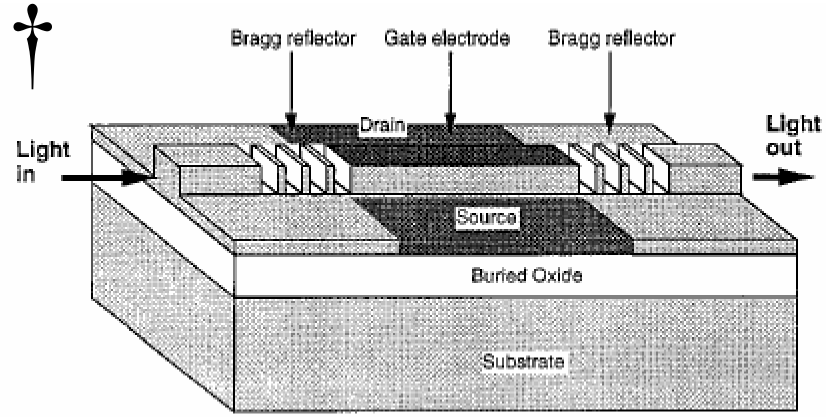
† C. A. Barrios, V. R. Almeida, and M. Lipson, "Low Power-Consumption Short-Length and High-Modulation-Depth Silicon Electrooptic Modulator", J. of Lightwave Tech., Vol. 21, No. 4, pp. 1089-1098, April, 2003.

Optical Structures

*



†



- Mach-Zehnder interferometer
- Destructive interference
  - condition: $\Delta\phi = \pi$

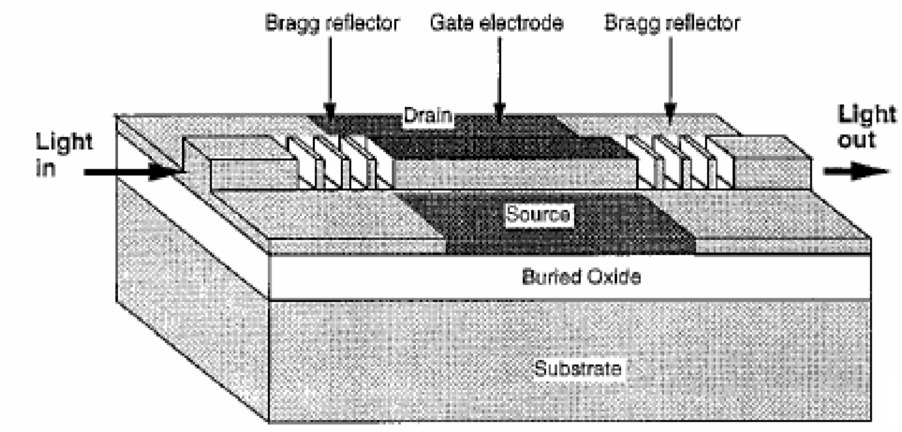
$$L = \lambda/(4*\Delta n_{eff})$$

- Micro-resonator
- Wavelength selective
- Compact

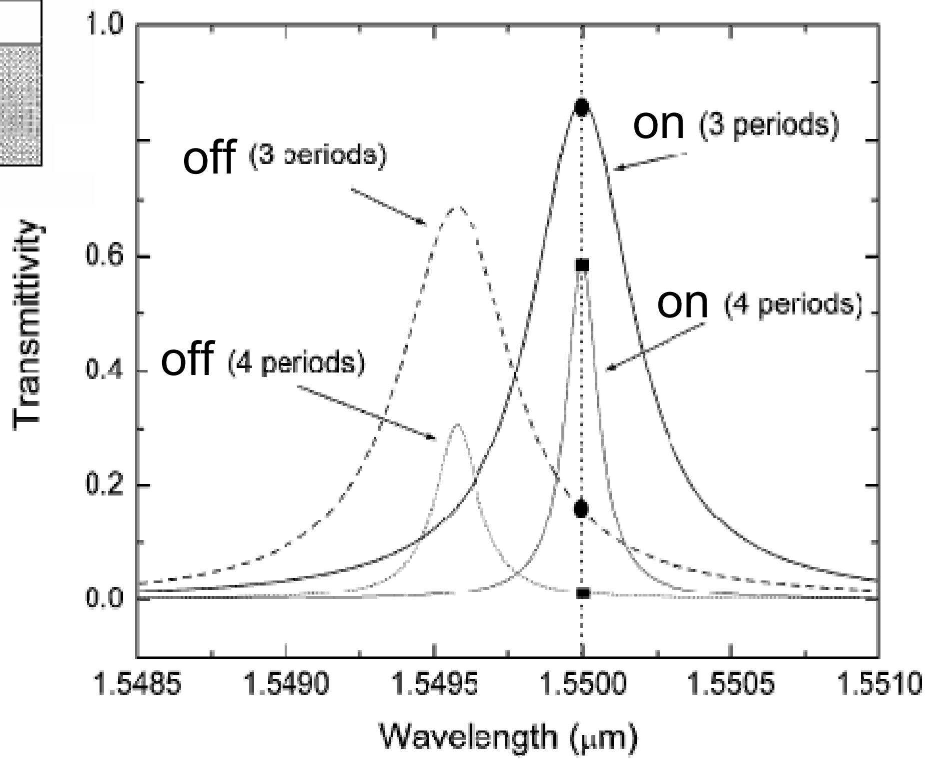
* A. Liu *et al*, "A High-Speed Silicon Optical Modulator Based on Metal-Oxide-Semiconductor Capacitor", *Nature*, Vol. 427, pp. 615-618, February, 2004.

† C. A. Barrios, V. R. Almeida, and M. Lipson, "Low Power-Consumption Short-Length and High-Modulation-Depth Silicon Electrooptic Modulator", J. of Lightwave Tech., Vol. 21, No. 4, pp. 1089-1098, April, 2003.

Optical Part: Microresonator



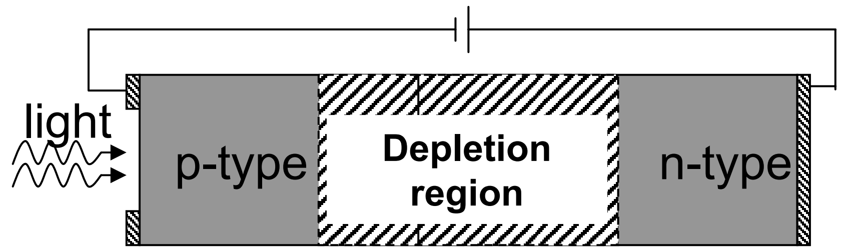
- Compact
- Wavelength selective



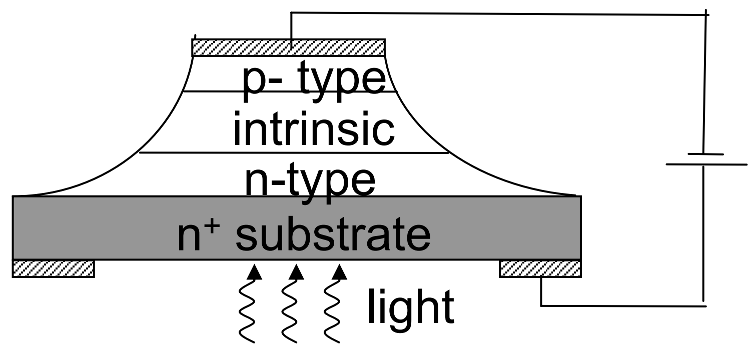
* C. A. Barrios, V. R. Almeida, and M. Lipson, "Low Power-Consumption Short-Length and High-Modulation-Depth Silicon Electrooptic Modulator", Journal of Lightwave Technology, Vol. 21, No. 4, pp. 1089-1098, April, 2003.

Category of Photodetectors

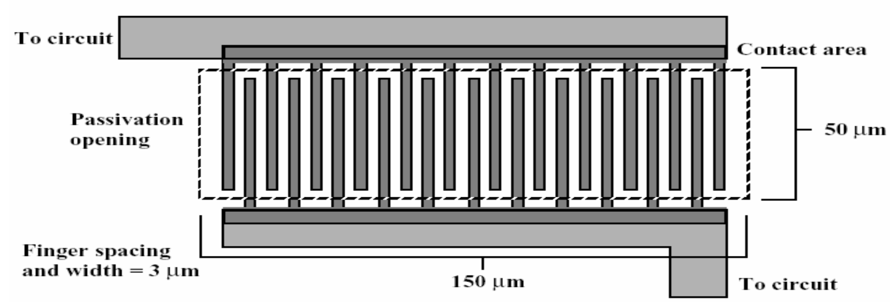
- p-n Photodiodes



- p-i-n Photodiodes

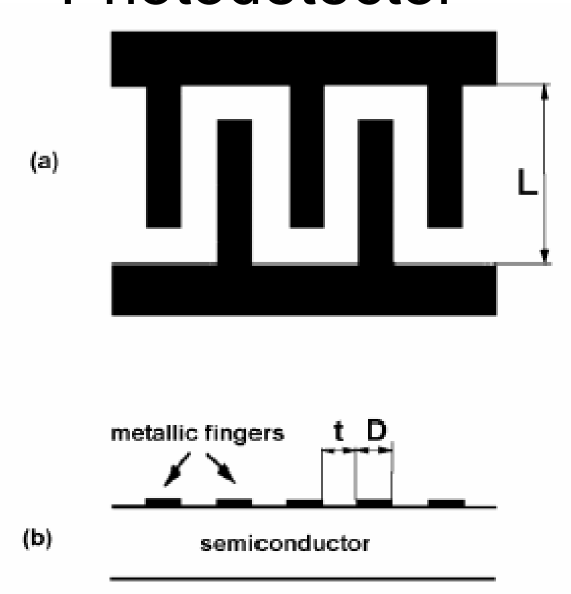


- Metal-semiconductor-metal (MSM)
  - High speed
  - Easy fabrication
  - Reasonable quantum efficiency



Delay and power of an optical receiver

Photodetector



- For MSM interdigitated photodetector, response time is

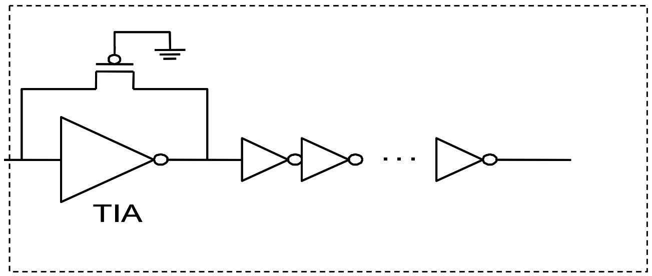
  $T_r = (\tau_{tr}^2 + \tau_{RC}^2)^{1/2}$

  – Transit time $\tau_{tr} = t\chi/2V$,
    - V: carrier drift velocity
    - X: drift distance corrective coefficient

  – RC response time $\tau_{RC}=2.2RC$

  Delay is $T_D=0.315T_r$

Receiver circuits

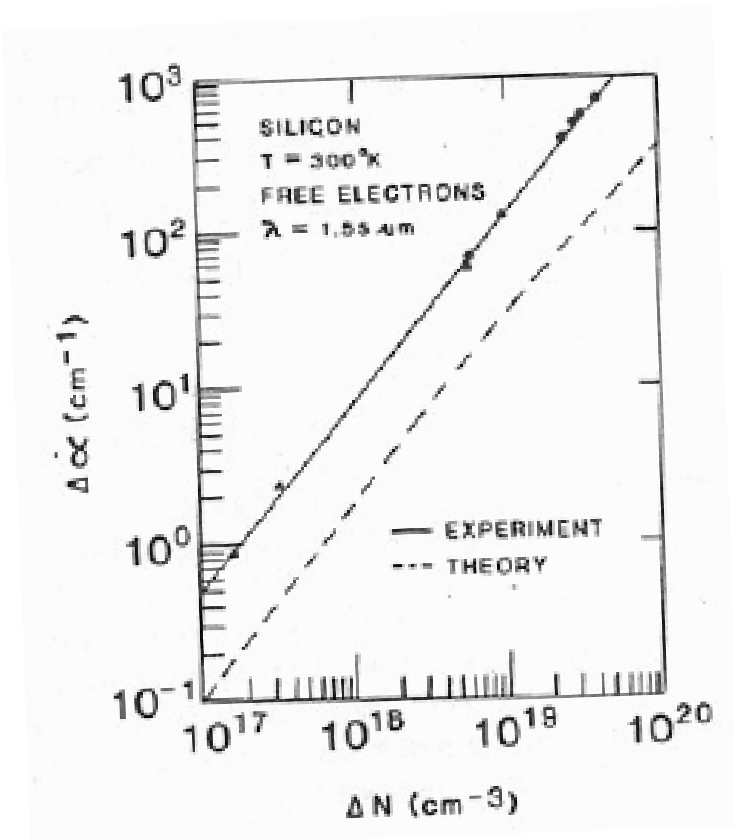


Receiver Circuits

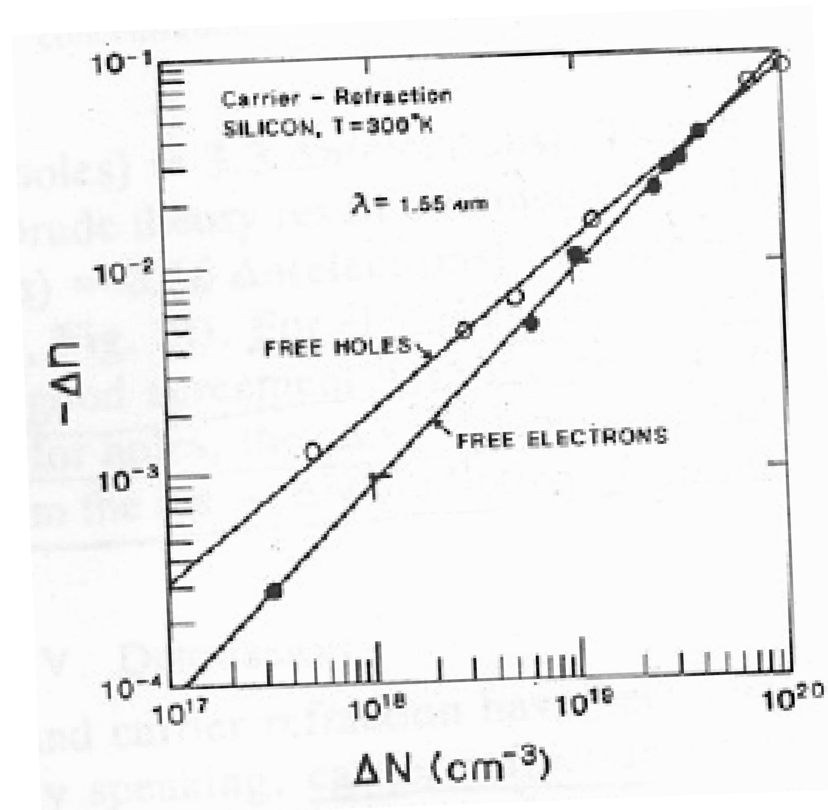
- Delay is $T_D=0.693 / (2 \pi \Delta f)$
- Power is

  $P_{rec} = (W_{TIA}/W_{min})I_{dsat0}V_{dd} + (I_{bias}V_{dd} + I_{ph}V_{bias})/2 + N_{inv}I_{dsat0}V_{dd}$

Electro-optical effects in silicon



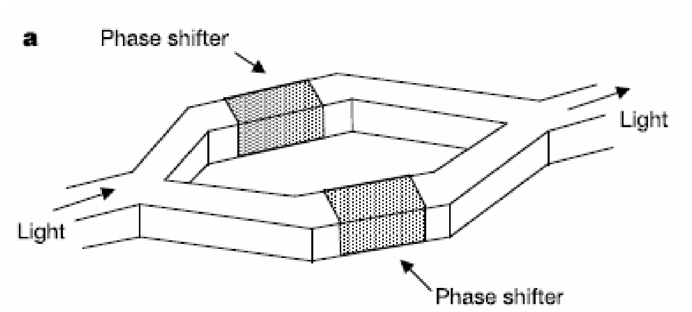
Electroabsorption

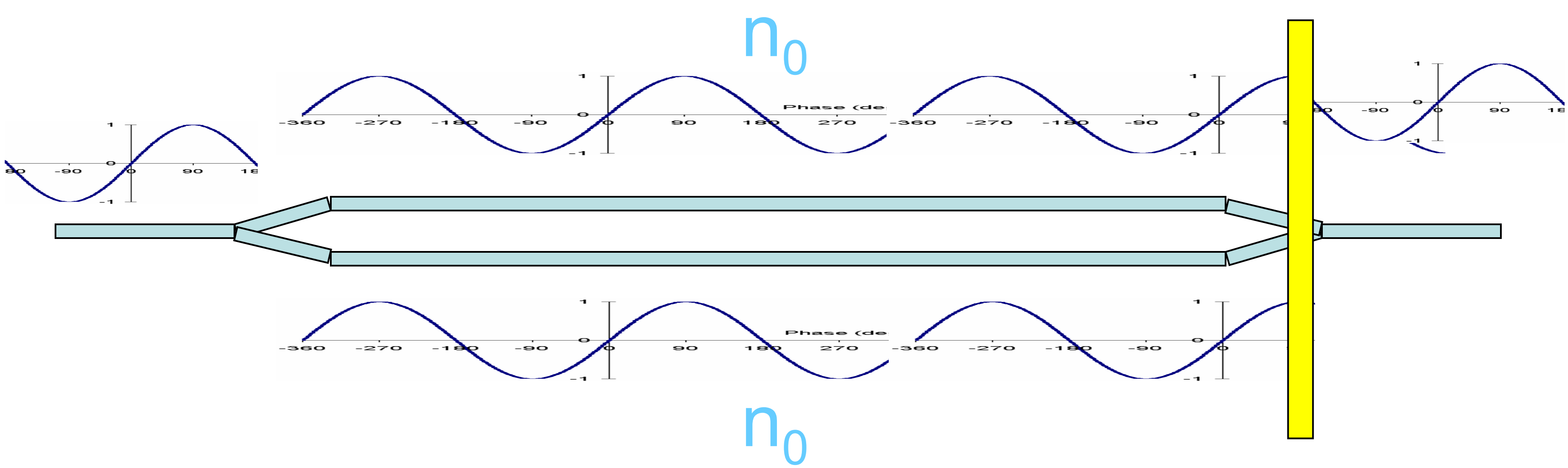


Electrorefraction

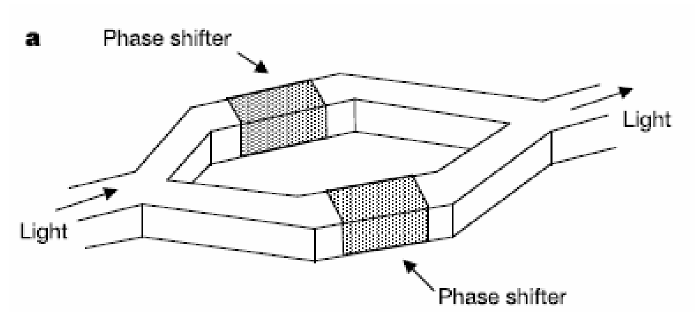
R. A. Soref, “Silicon-based optoelectronics,” Proc. IEEE, vol. 81, pp. 1687–1706, Dec. 1993

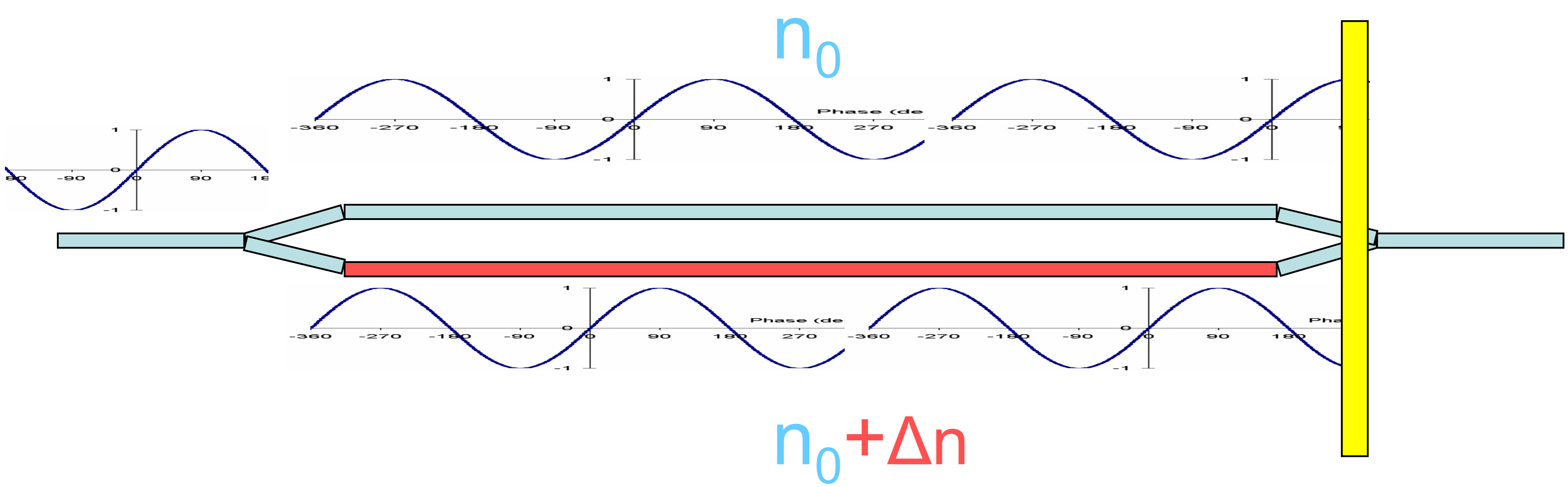
Optical modulator – Mach-Zehnder interferometer structure





Optical modulator – Mach-Zehnder interferometer structure





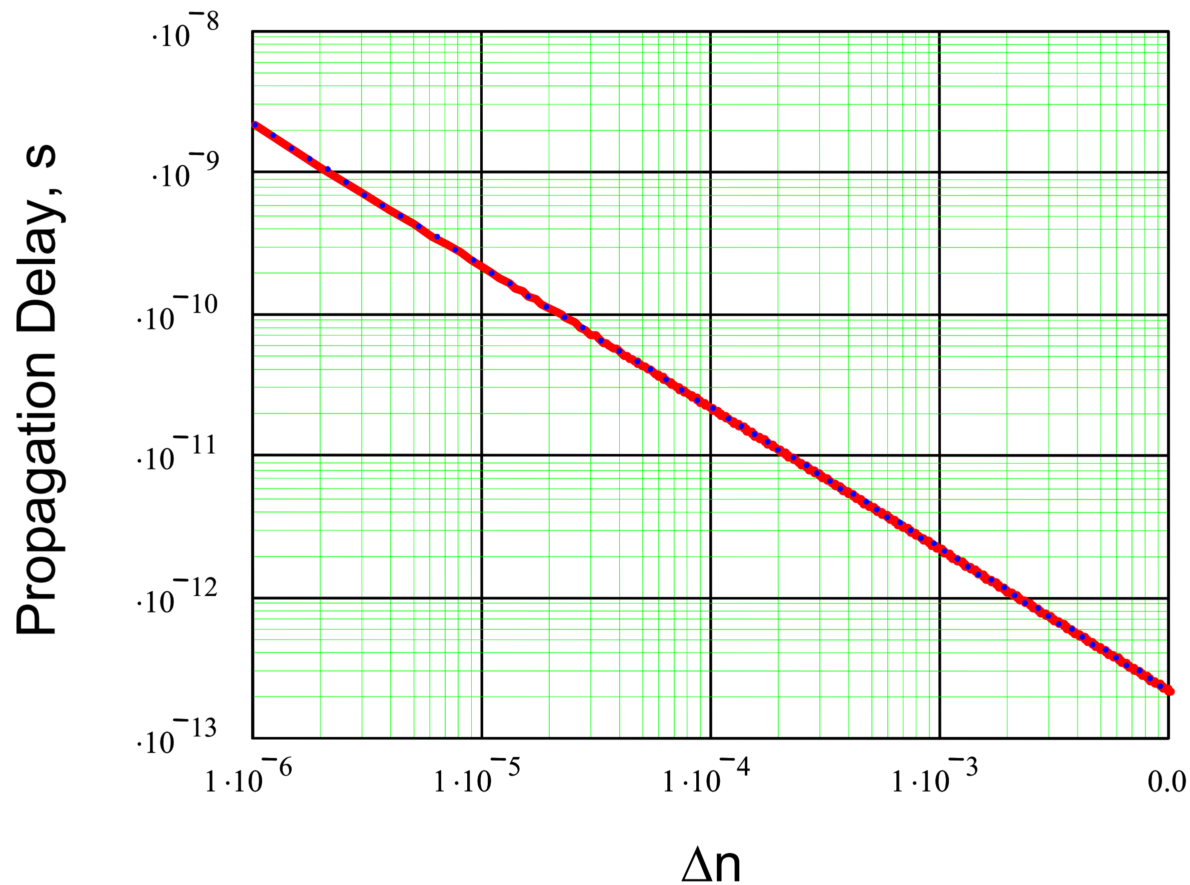
Propagation delay – both structures

Blue line: M-Z interferometer

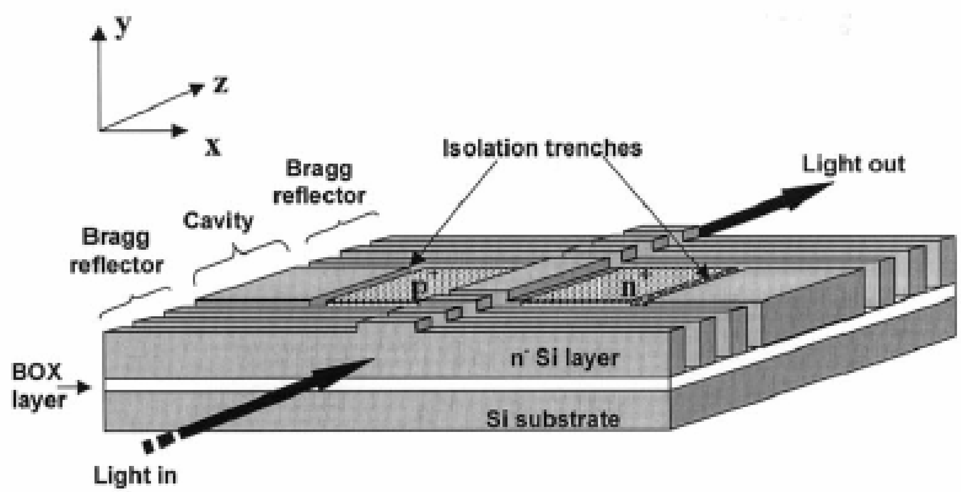
$T_{pi} = L/c^*n_{si}$

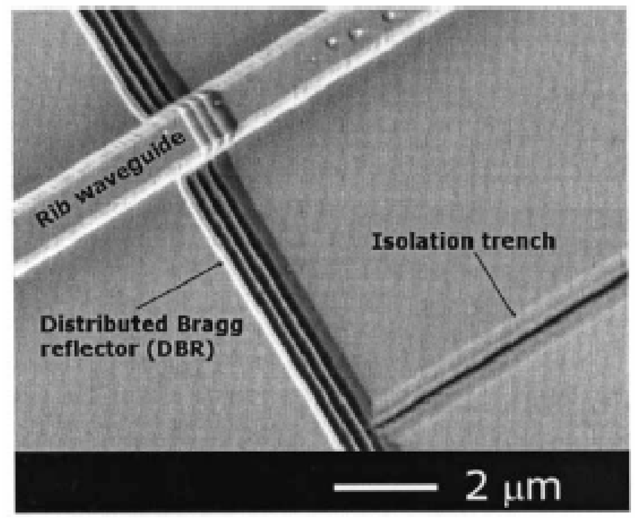
Red line: Micro-resonator

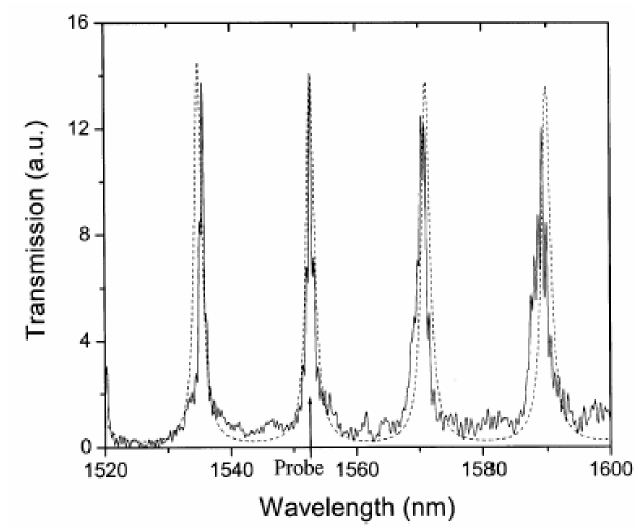
$$\Delta_t \Delta_\Omega \geq \frac{1}{2}$$



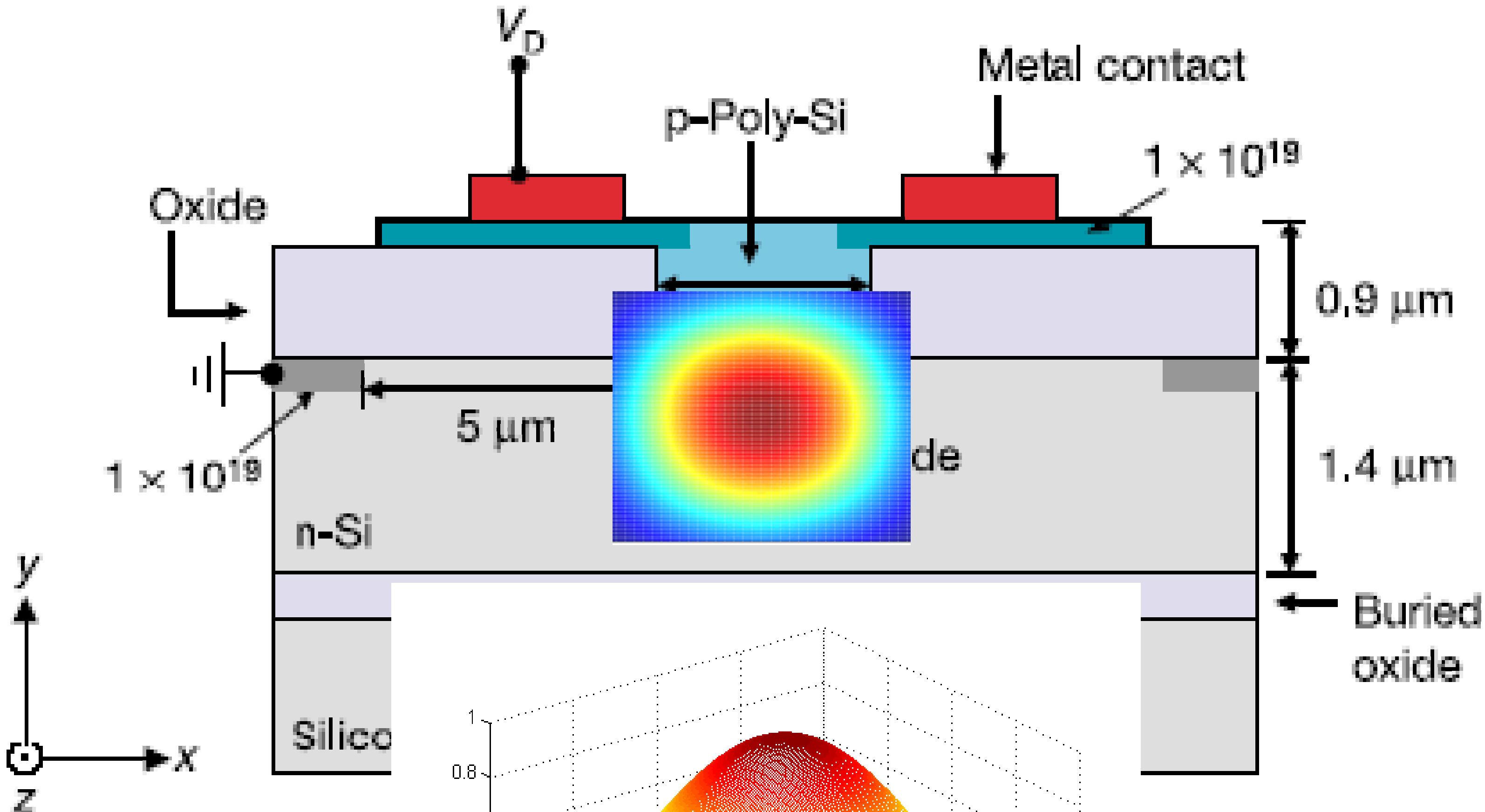
Microcavity-based modulator (Barrios et.al)

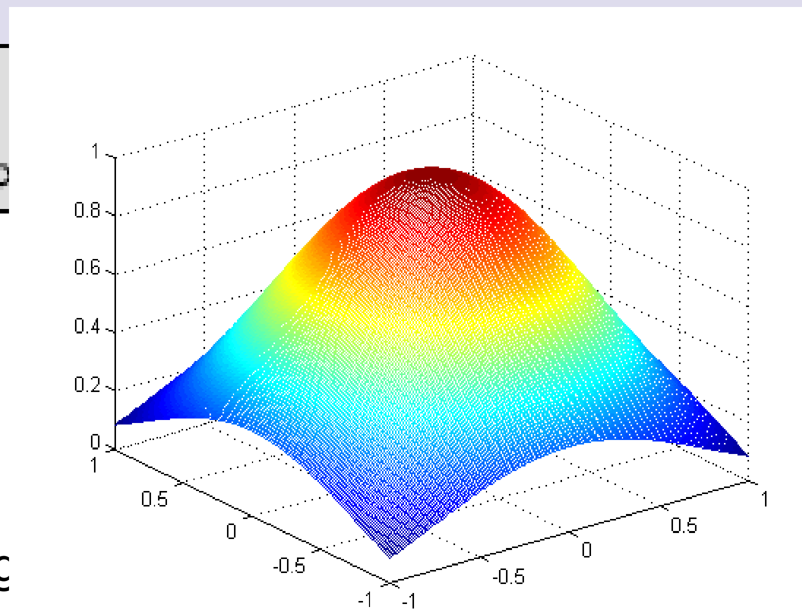






- **Size (20 µm)**
- **Power consumption (mWs)**
- **CMOS compatible**
- **Speed (injection-based)**





Assumption 1:

Modulator is a sing he fundamental
mode field can be

$$E_z(x,y) = \sin(\frac{a-x}{2a}\pi)\sin(\frac{a-y}{2a}\pi)$$