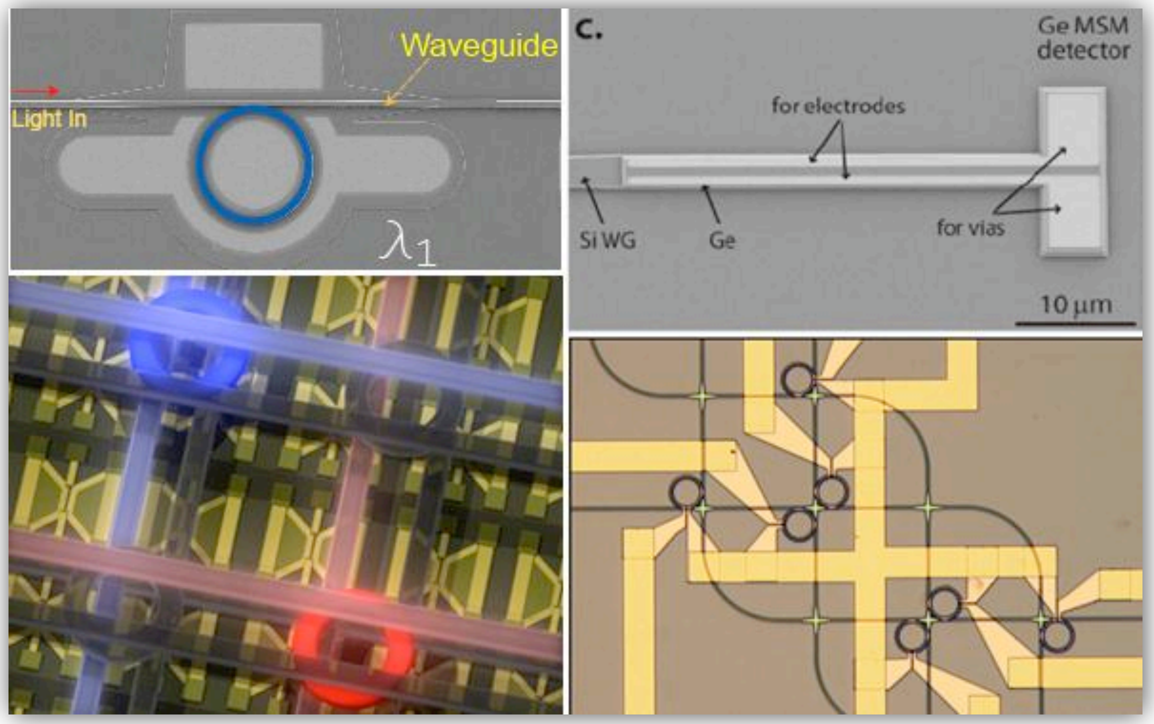
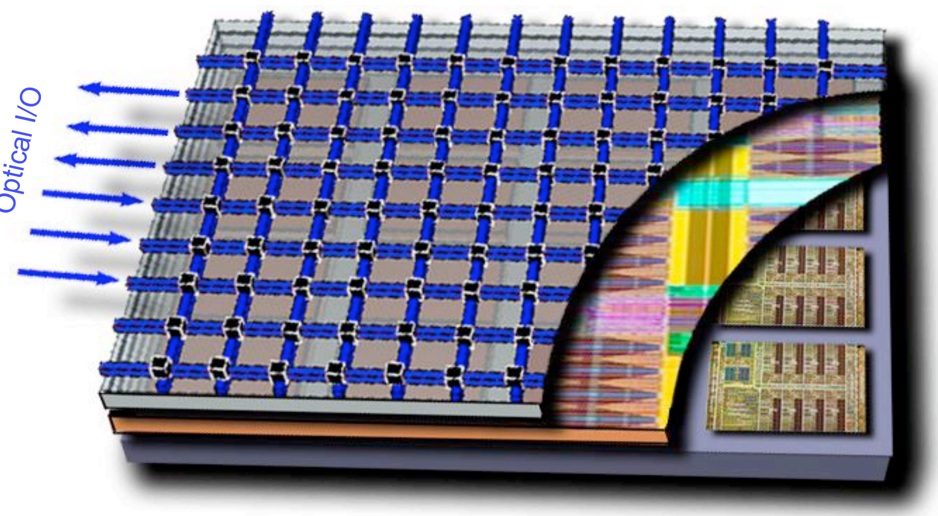
Scaling Silicon Nanophotonic Interconnects

using compact, high speed, multi-wavelength devices

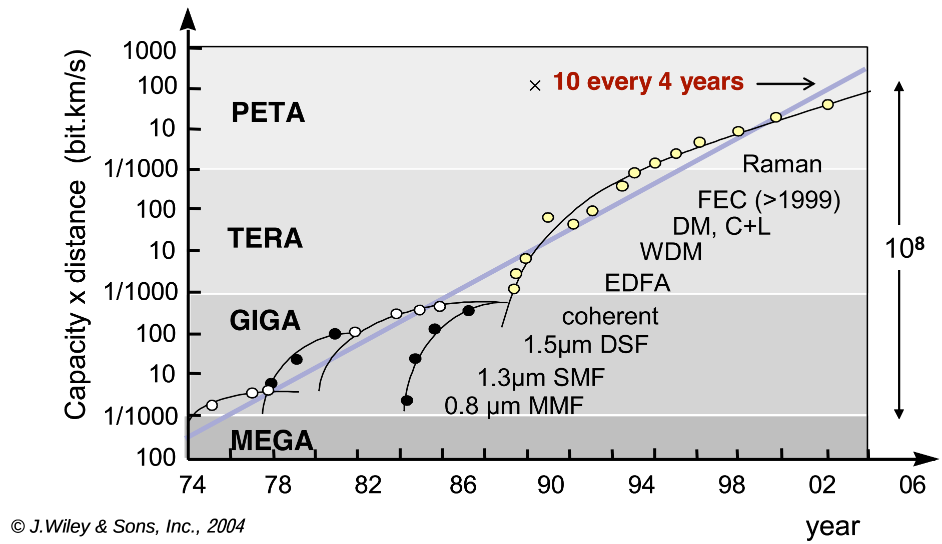


Sasikanth Manipatruni, Michal Lipson

Silicon Nanophotonics: Opportunities



High Performance Computing

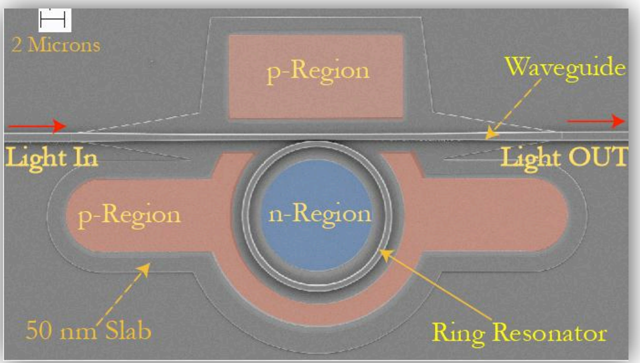


Evolution of telecommunications; E. Desurvire, 2006

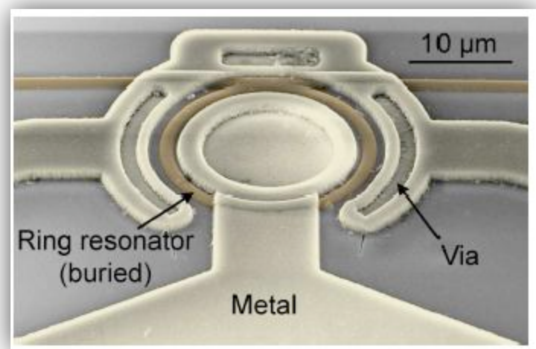
Scalable Devices for Web 3.0

IBM, Oracle-Sun, HP, Intel, Alcatel, Corning, Sandia Labs,Fujitsu, NTT, Hitachi, A*STAR, IMEC-Belgium, Luxtera, Kotura

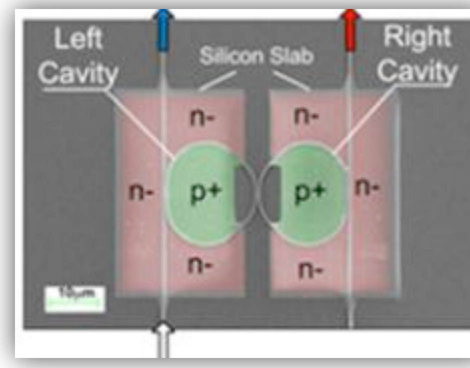
Silicon Photonic Devices :
Interconnect Integrated Devices



Silicon Microring Modulator

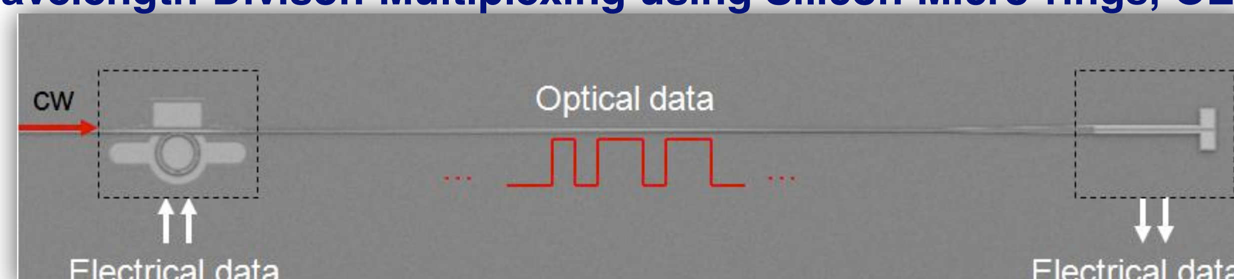


3D Poly Modulator OE '09



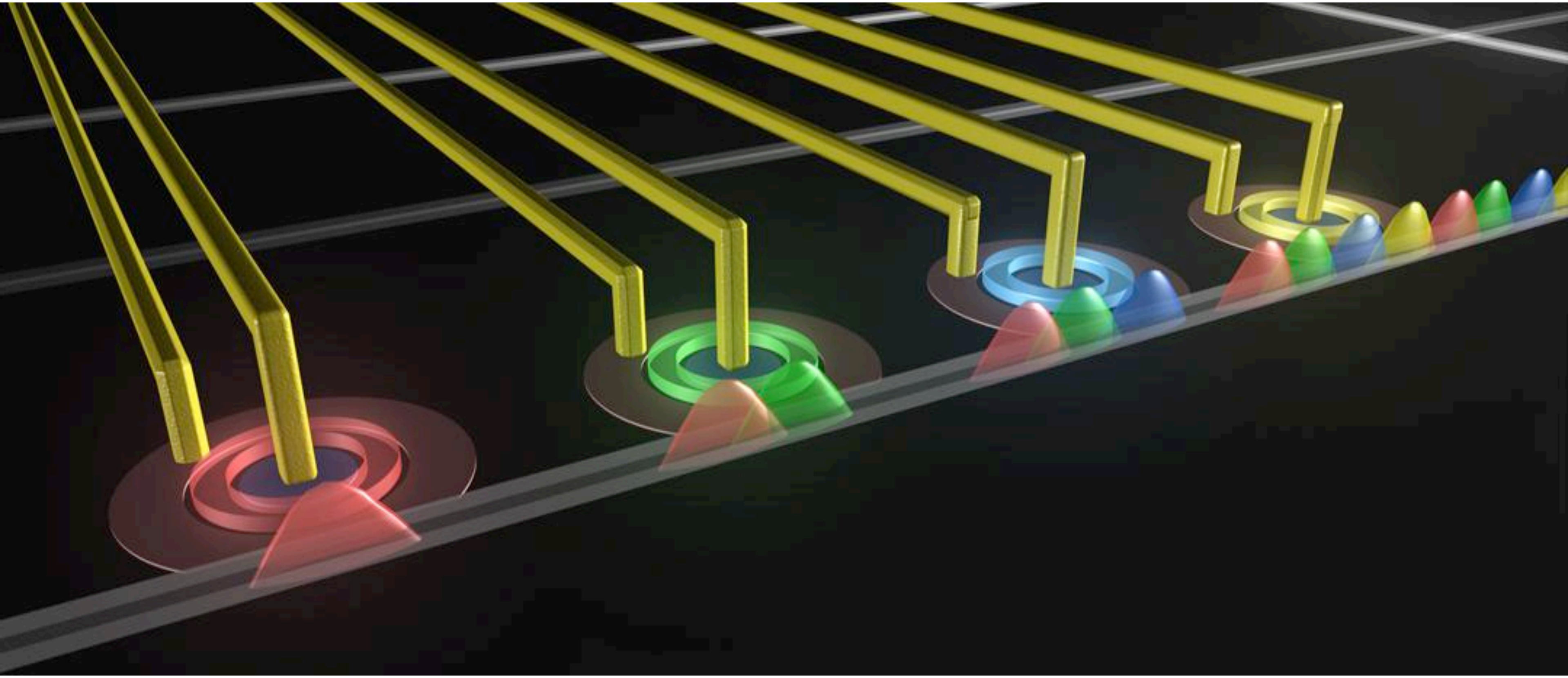
Broadband Switch OE '09

Wavelength Divison Multiplexing using Silicon Micro-rings, OE'2010

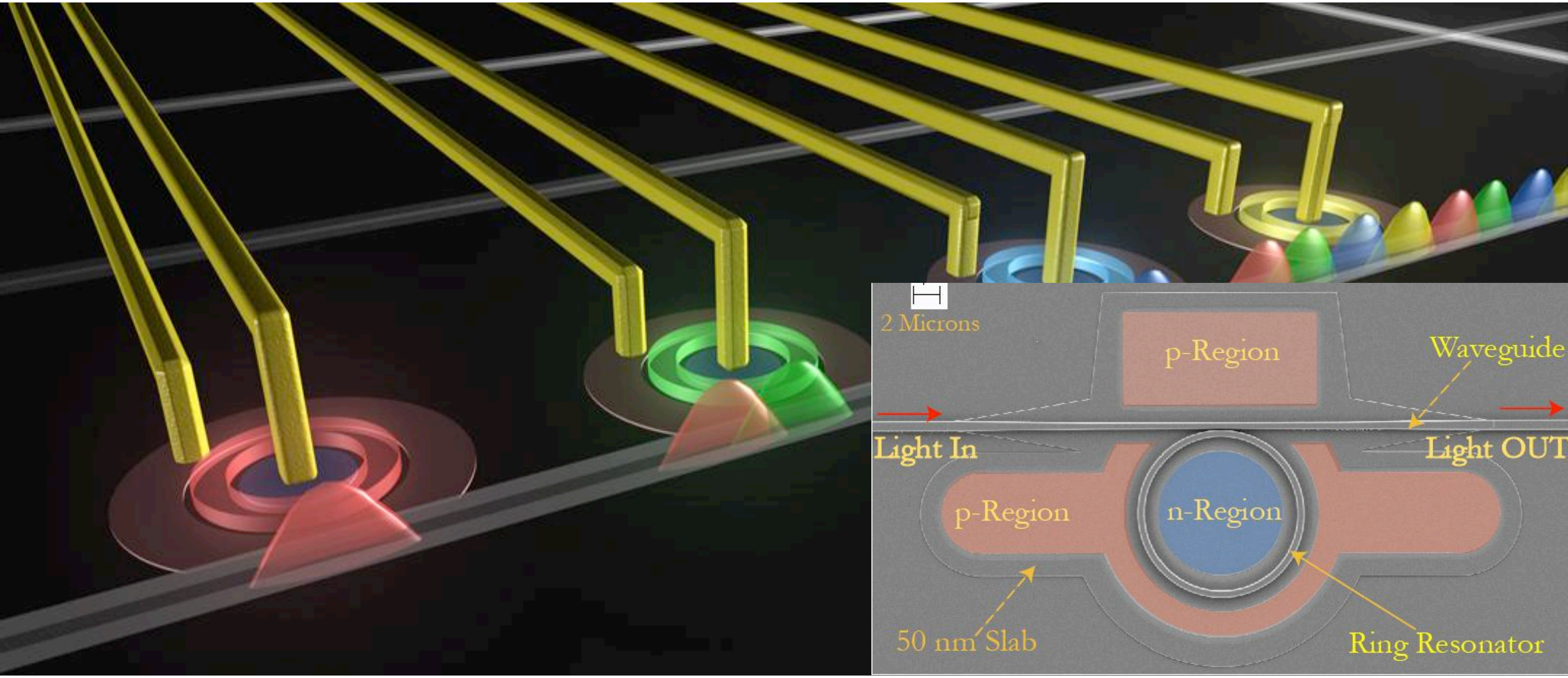


Complete Interconnect OE '09

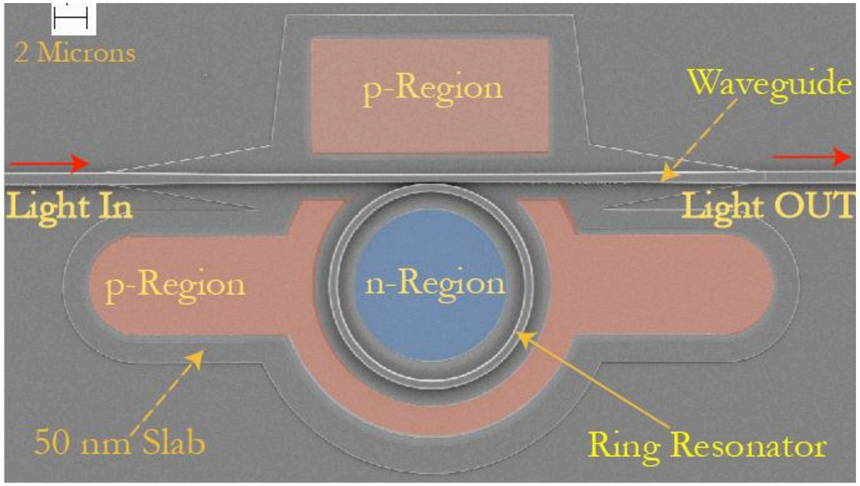
Resonant Silicon Electro-optic Modulators

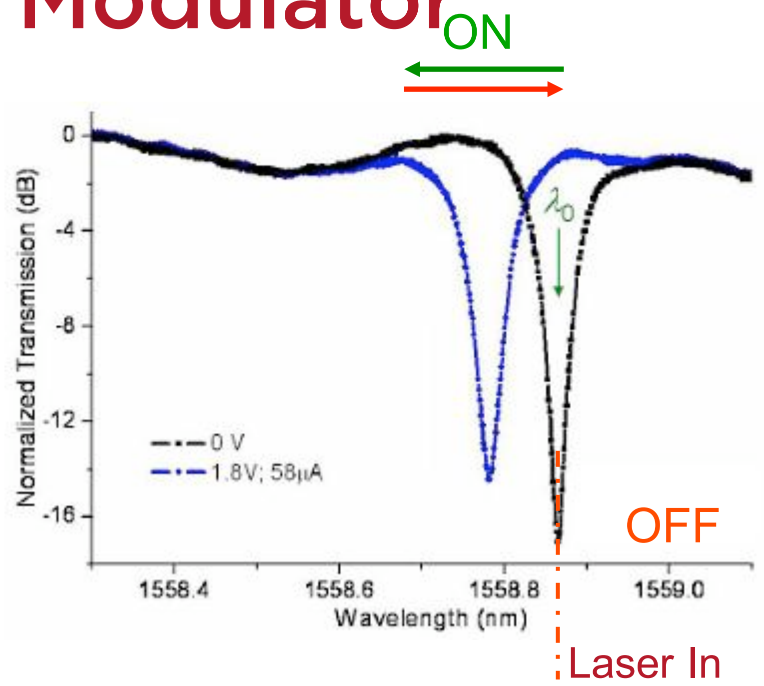


Resonant Silicon Electro-optic Modulators



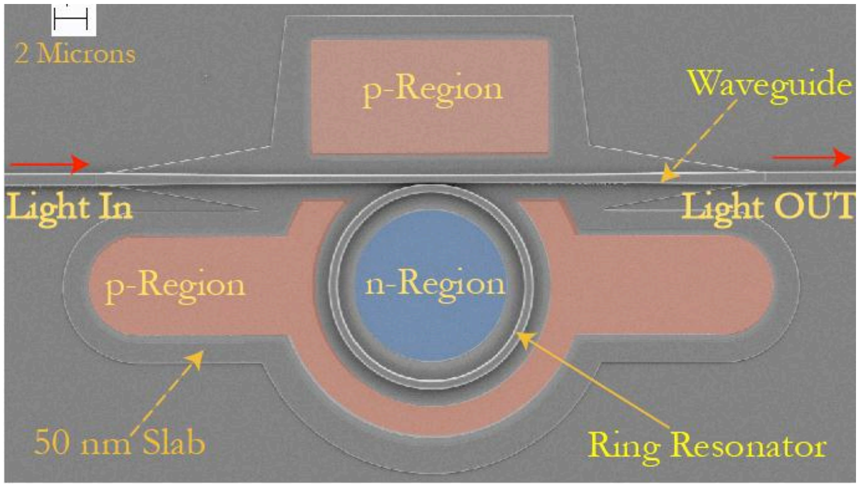
Micro-ring Silicon Electro-optic Modulator

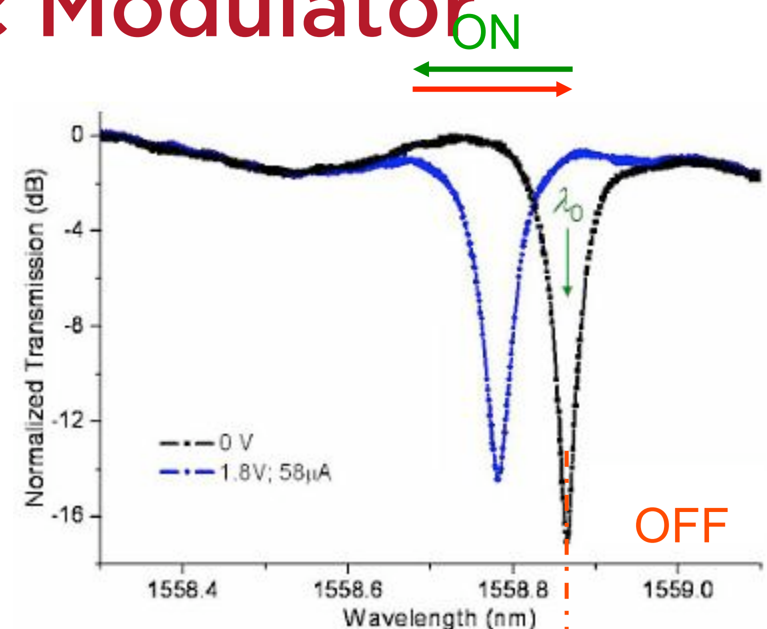


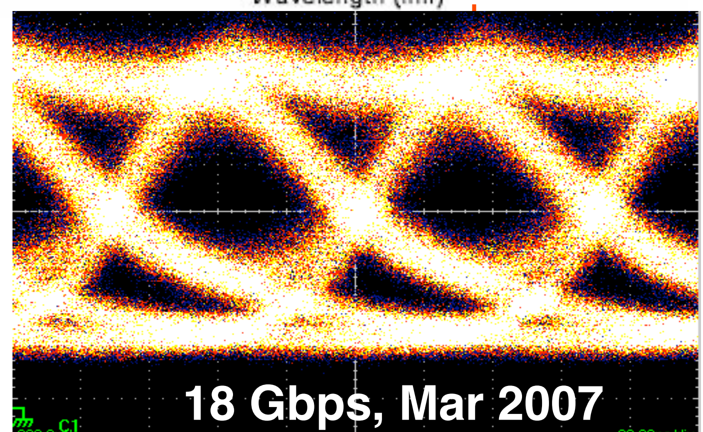


- Index changes are translated into large modulations in output power.
- The modulated light can be switched on and off at a high speed.

18 Gb/s micro-ring Silicon Electro-optic Modulator







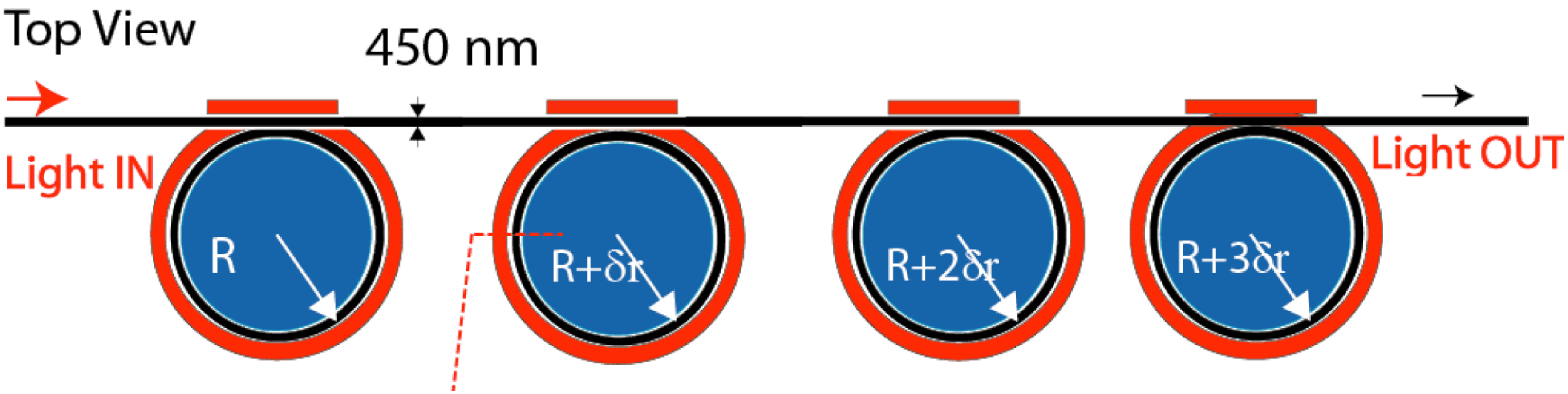
Fastest Modulation Rate on Silicon using Micro-rings

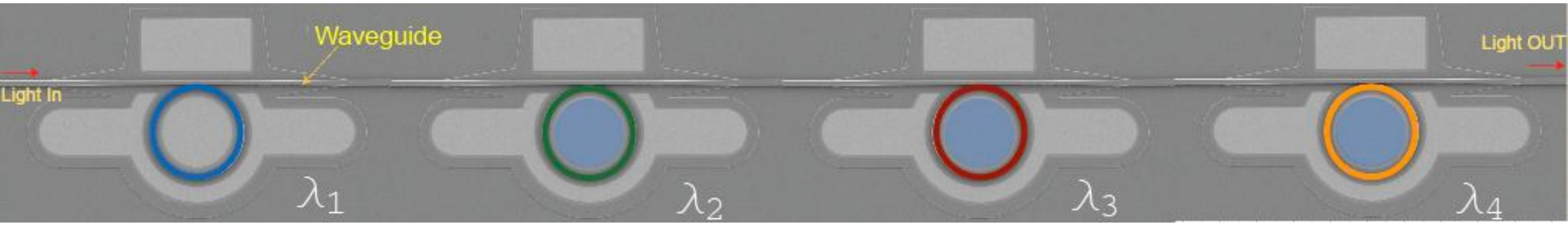
S. Manipatruni, M. Lipson et al LEOS 2007

S. Manipatruni, Q.Xu, M. Lipson Opt. Express Vol. 15, No. 20, (2007)

Scaling the Modulation Bandwidth

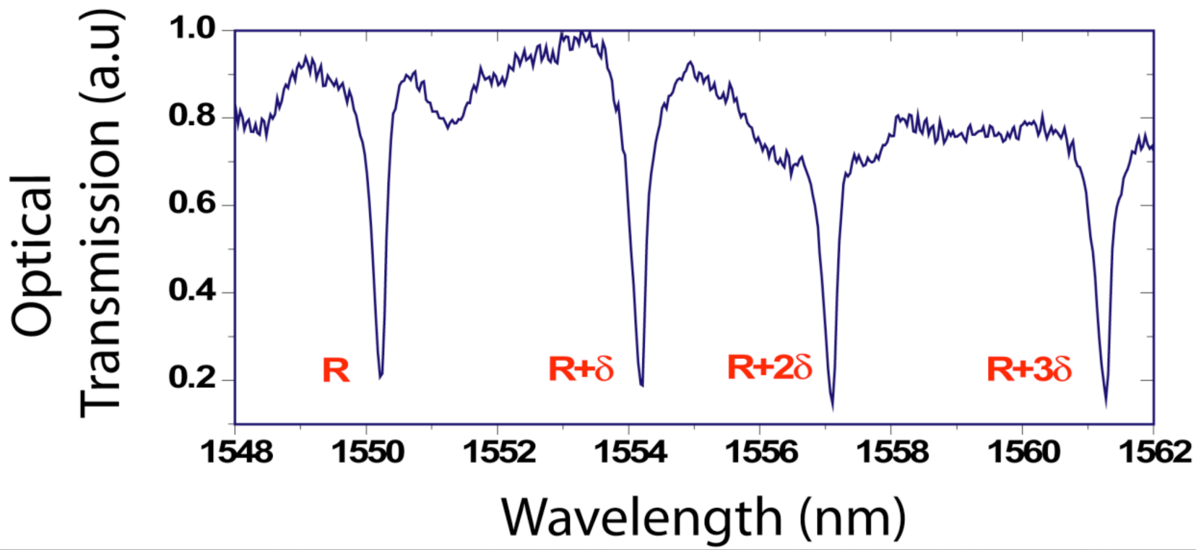
50 Gbit/s Wavelength Divison Multiplexing System

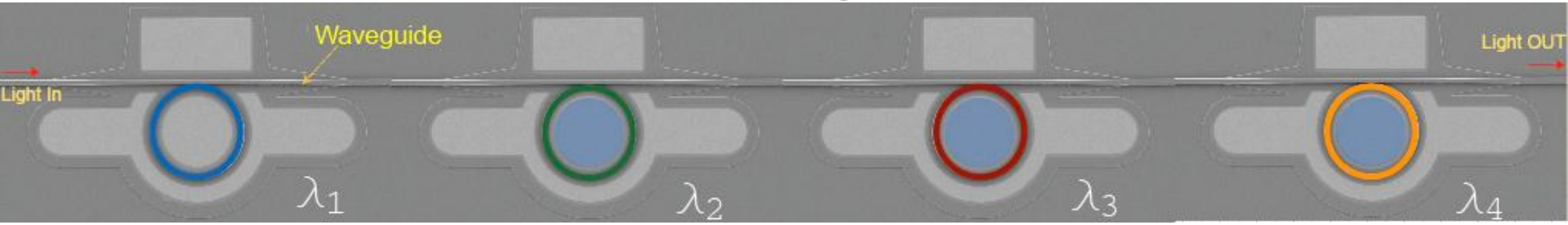




S. Manipatruni, L. Chen and M. Lipson, "Ultra Wide Band WDM using Silicon Micro-ring Modulators " Optics Express 2010

50 Gbit/s Wavelength Divison Multiplexing System





S. Manipatruni, L. Chen and M. Lipson, "Ultra Wide Band WDM using Silicon Micro-ring Modulators " Optics Express 2010

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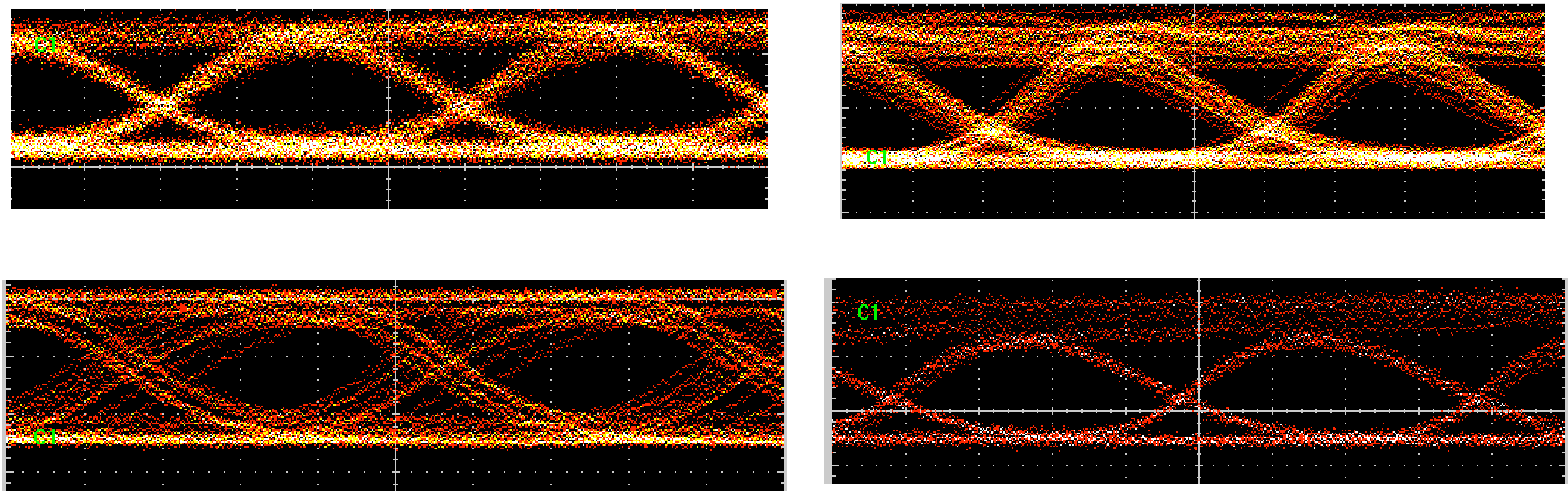


Highest Modulation Bandwidth on Silicon using Microrings

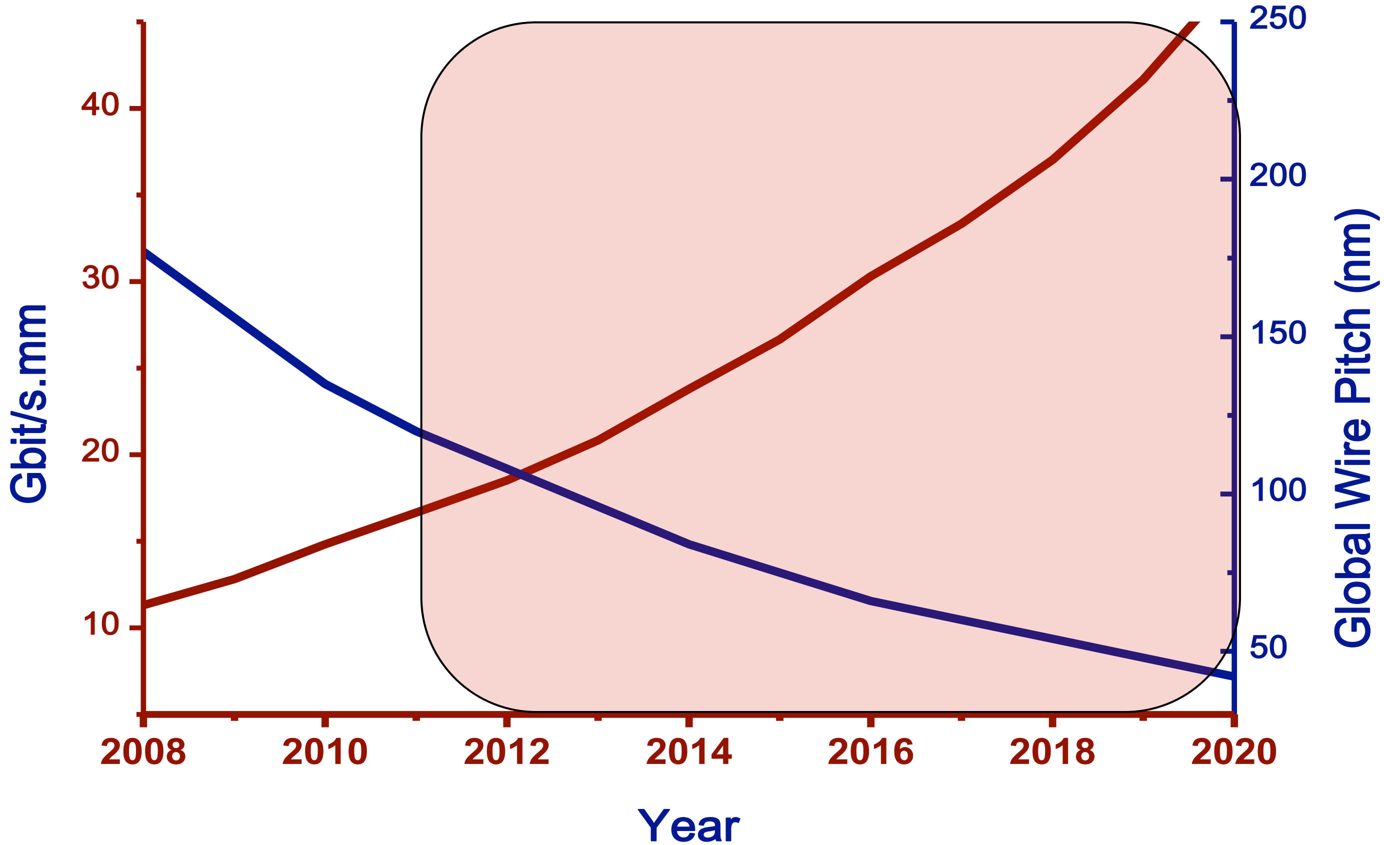
S. Manipatruni, L. Chen and M. Lipson, "Ultra Wide Band WDM using Silicon Micro-ring Modulators " Optics Express 2010

Bandwidth Density for Future Microprocessors

$$\beta = \frac{kB}{g} = \frac{7.6kB}{\log_e\left(\frac{6.7z}{\lambda_0}\right)}$$

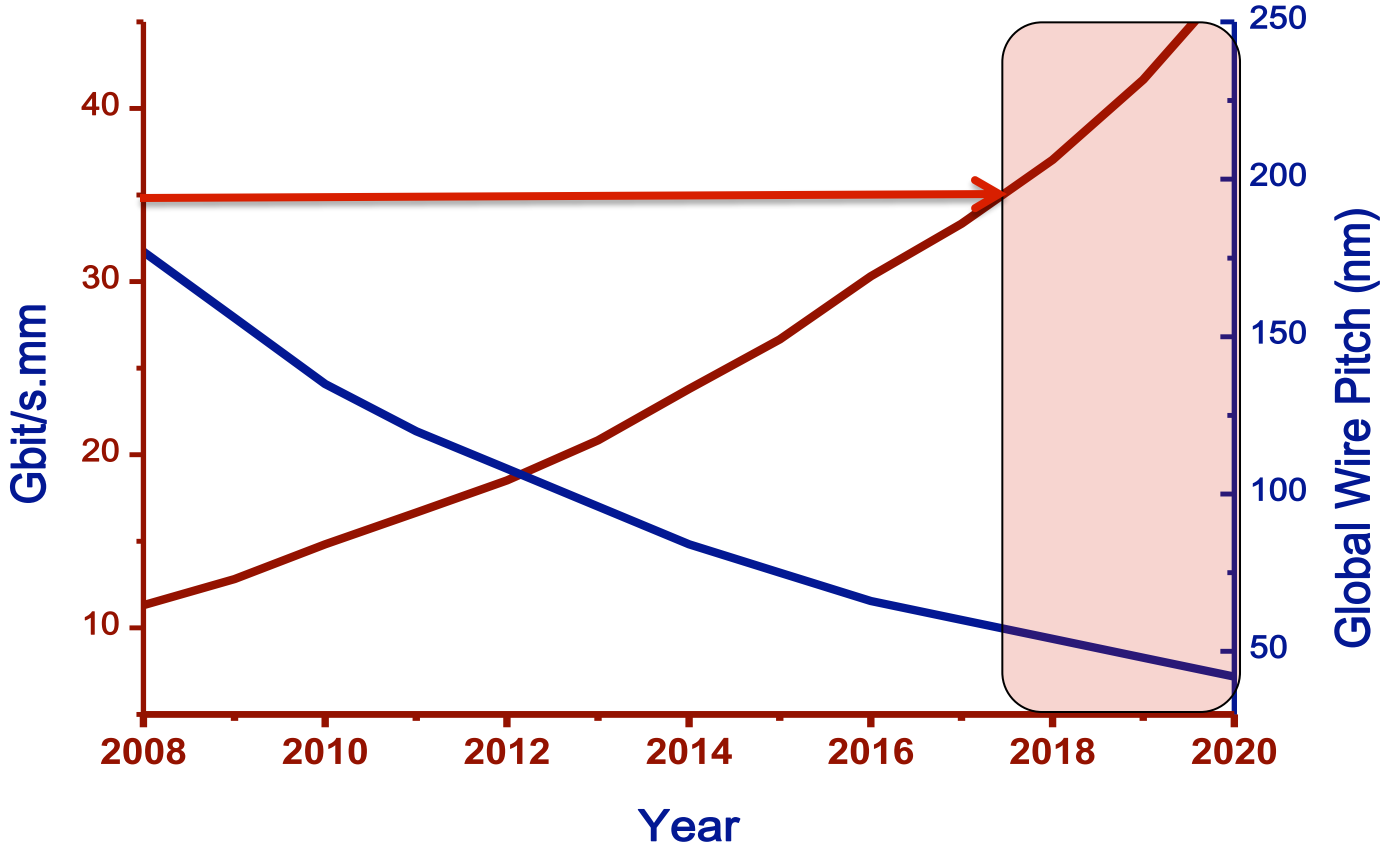
Bandwidth Density :
Data rate per micron pitch cross section

Bandwidth Density for Future Microprocessors



Scaling Density beyond 25 Gbit/s.micron
is a challenge with existing technologies.

Bandwidth Density for Future Microprocessors



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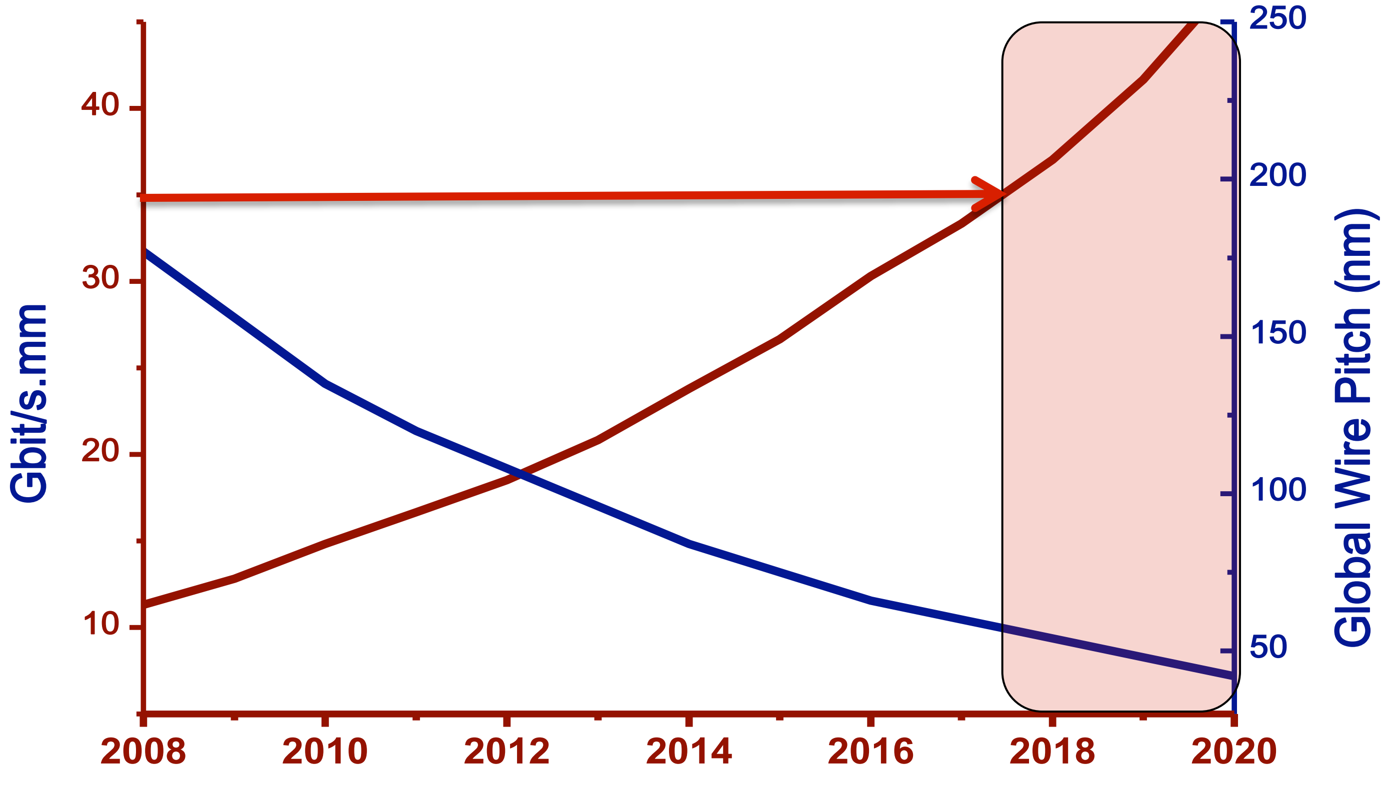
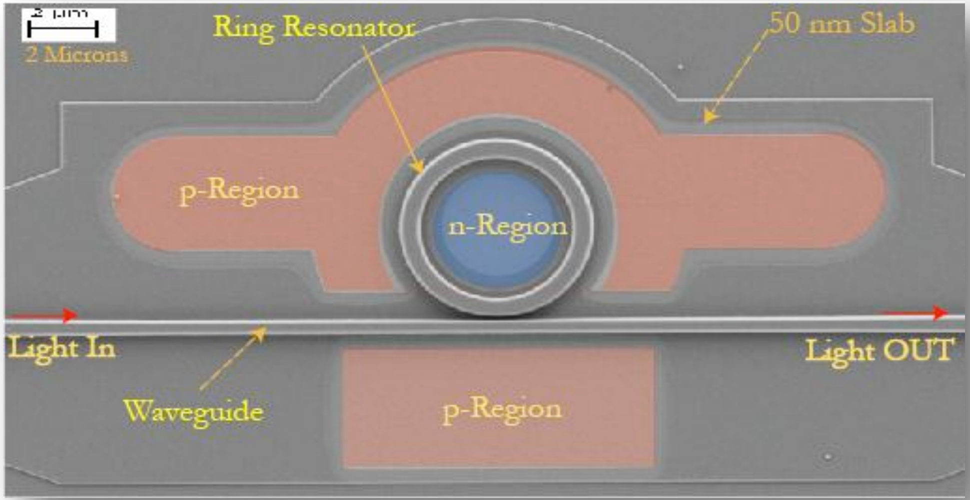
Bandwidth Density for Future Microprocessors



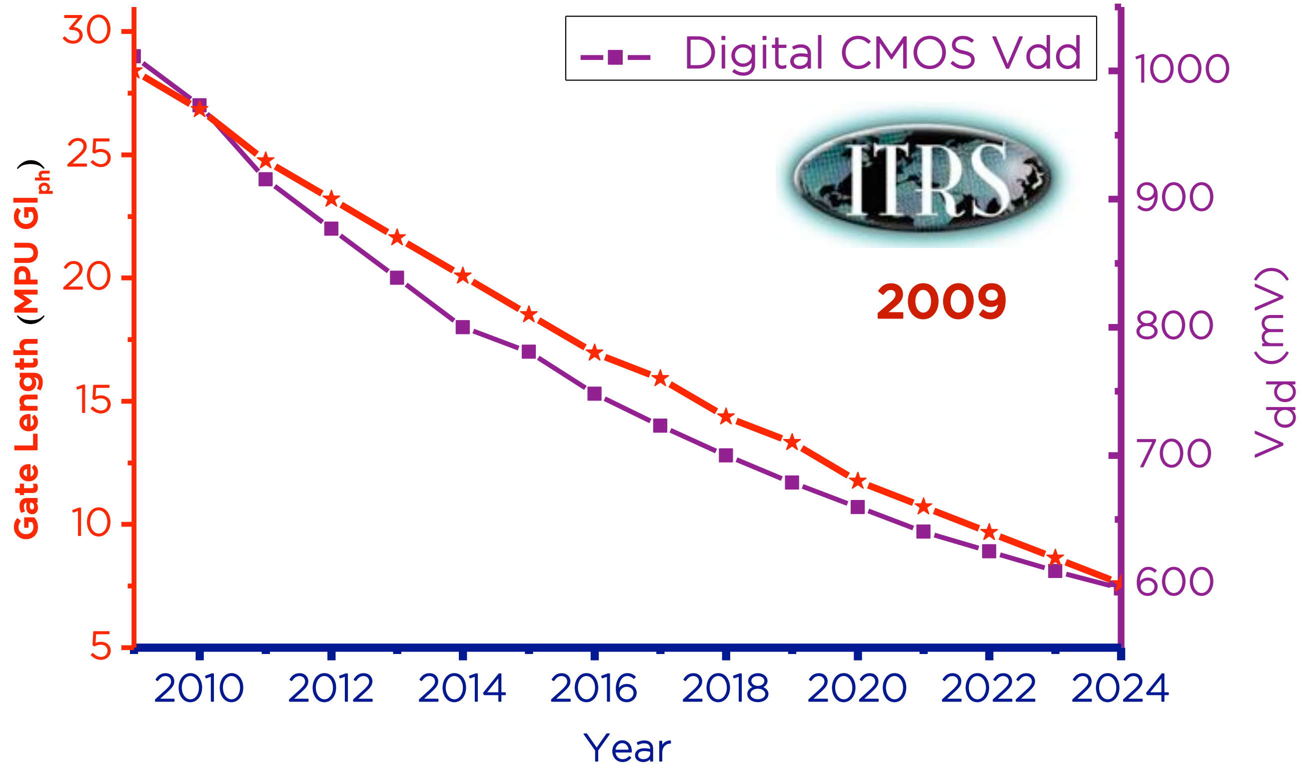
Here, we show a bandwidth capacity of 33 Gbit/s.μm and ~ 100 Tbit/s· mm² modulation density.

150 mV Silicon Electro-optic Modulator

Towards Direct Digital Logic Driven Modulators

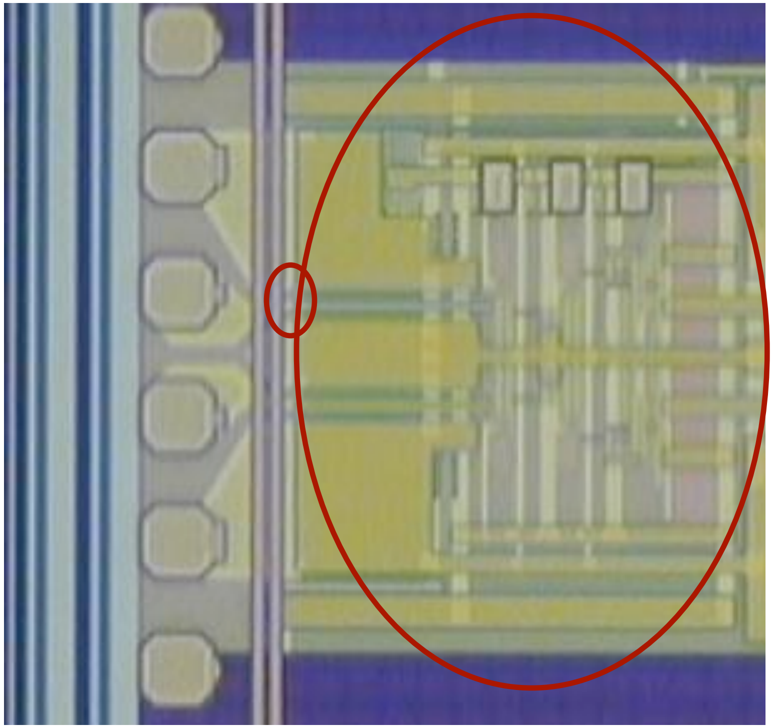


Voltage Scaling in Digital CMOS



Stringent conditions on voltage swing can be expected for future CMOS integration

Analog Driver Complexity

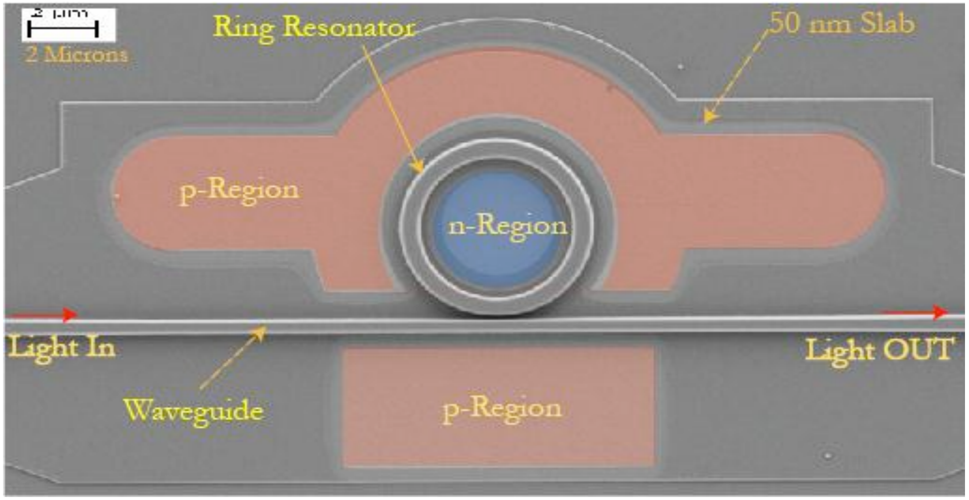


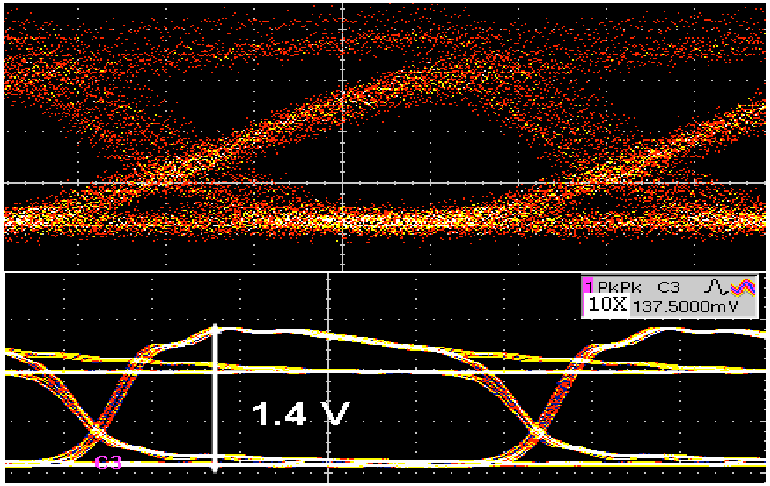
Analog drivers significantly
1. Decrease the bandwidth density
2. Increase the energy/bit

Luxtera 2005

Analog drivers limit the bandwidth density and the minimum energy achievable.

Scaling Micro-ring Modulators

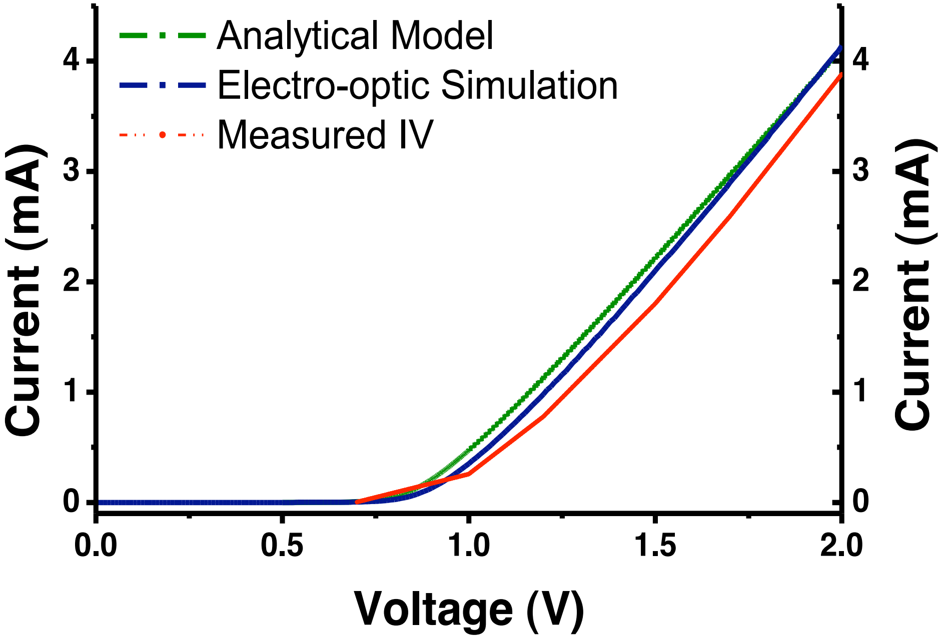




Silicon Micro-ring modulator with a modal volume of 2 Micron³

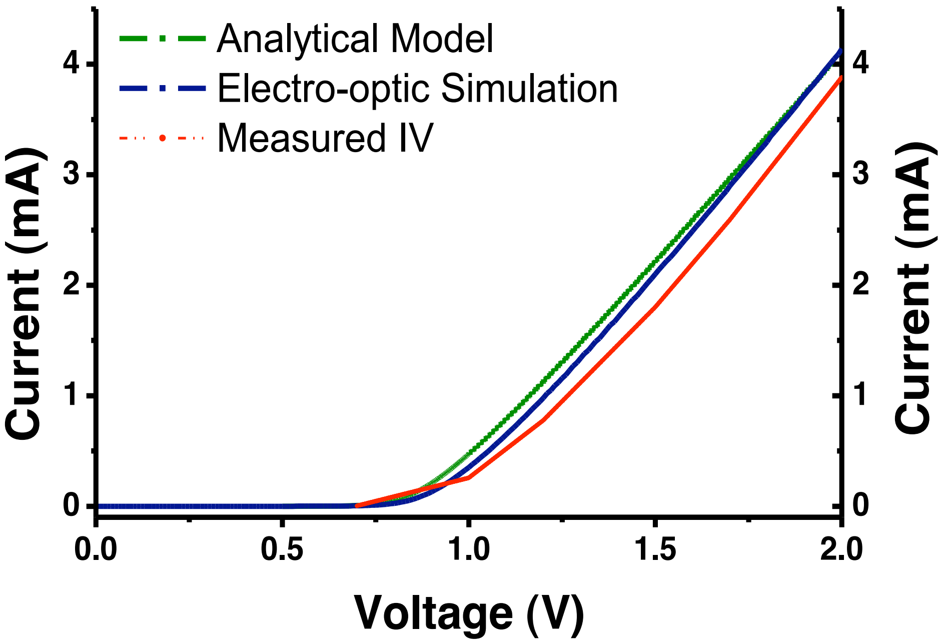
$$D_{optical} \equiv \frac{f}{Area} < \frac{V_{sat}}{nk}\left(\frac{\lambda}{2N}\right)^{-3}$$

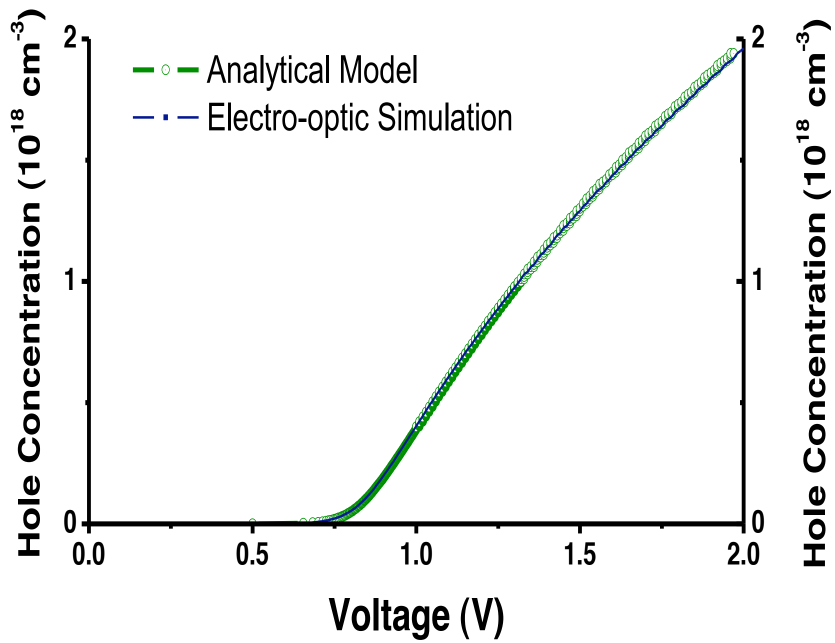
Optimum Driving Conditions for Carrier Injection Modulators



$$V(I) = V_t + IR + \frac{kT}{e\alpha}\log_e\left[\frac{I}{I_0}+1\right]$$

Optimum Driving Conditions for Carrier Injection Modulators

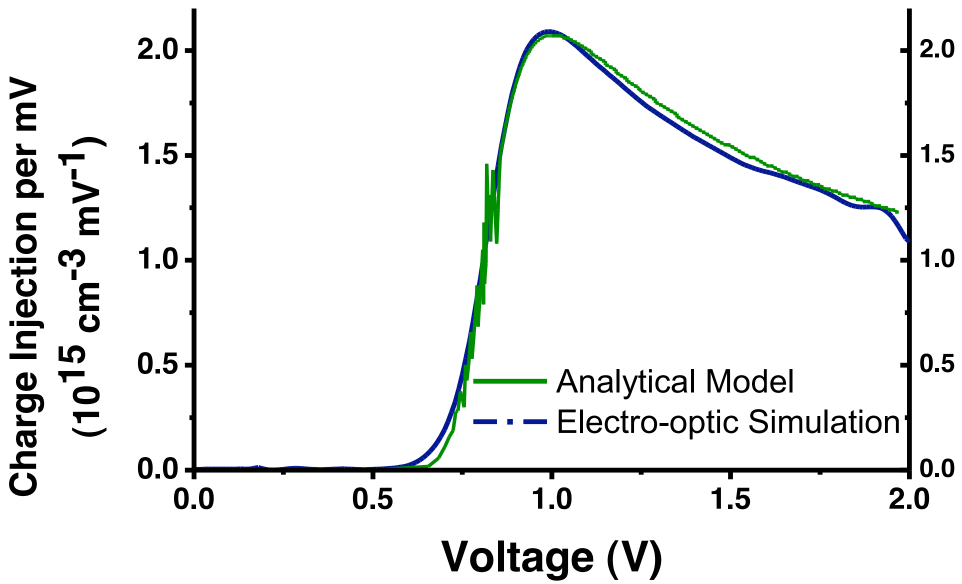


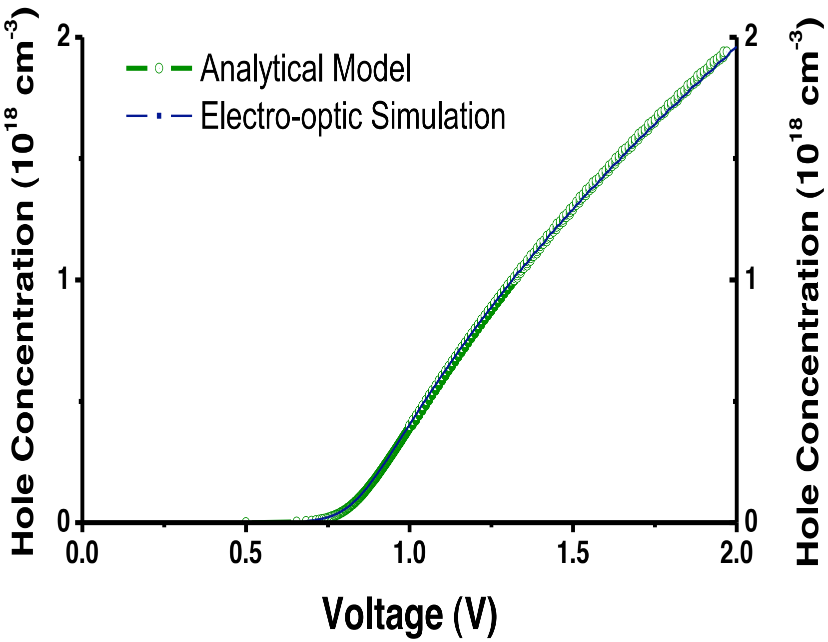


$$V(I) = V_t + IR + \frac{kT}{e\alpha}\log_e\left[\frac{I}{I_0}+1\right]$$

$$Q = I\tau_{recomb} = I\frac{\tau_0}{1+\left(\frac{Q}{Q_0}\right)^n}$$

Optimum Driving Conditions for Carrier Injection Modulators

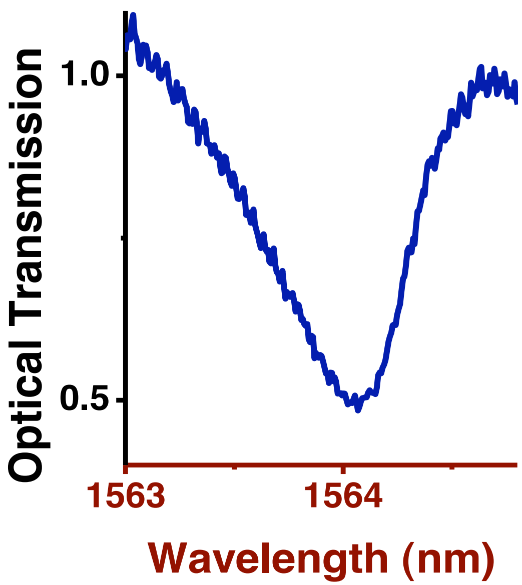


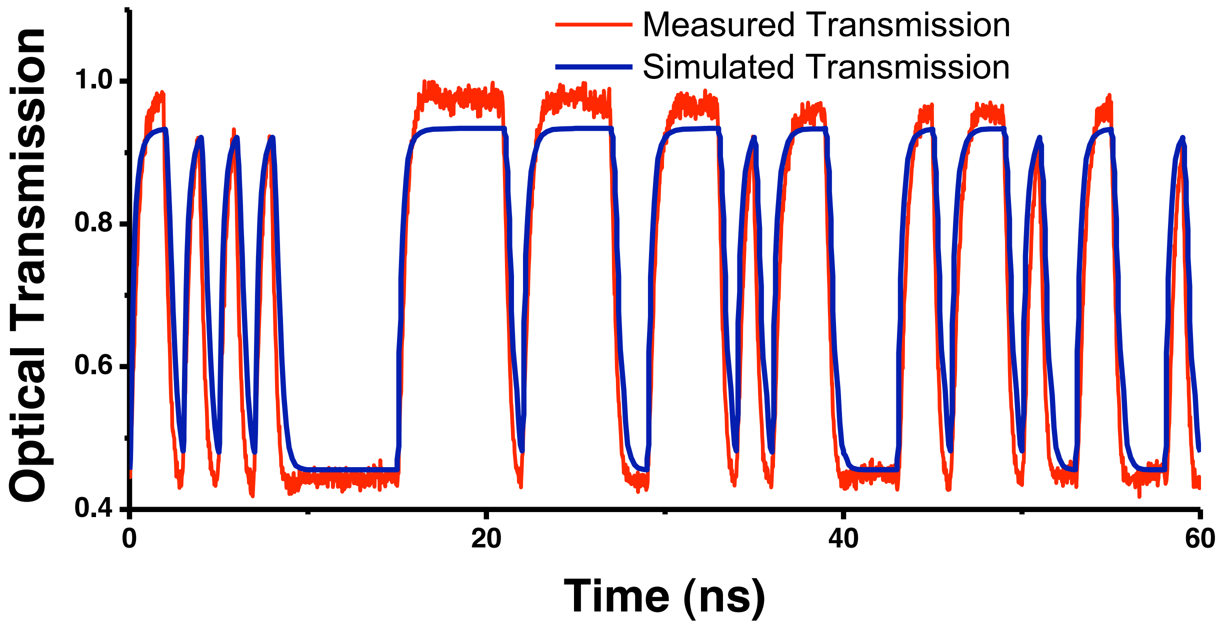


$$\frac{dQ}{dV} = G(V).\frac{\tau_0}{1 + \frac{1+Q}{Q_0}}$$

$$Q = I\tau_{recomb} = I\frac{\tau_0}{1 + \left(\frac{Q}{Q_0}\right)^n}$$

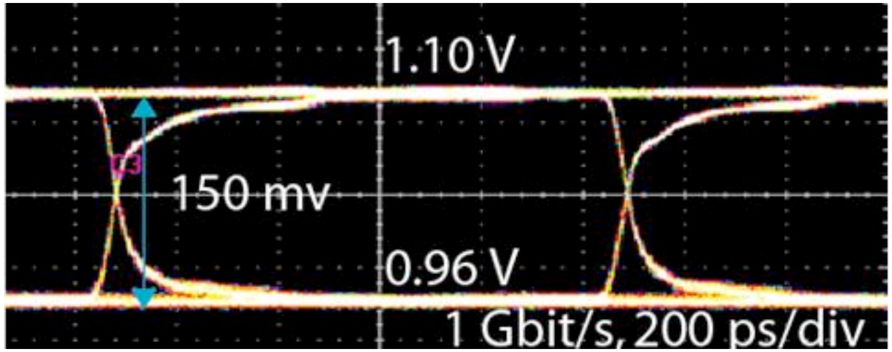
150 mV peak-peak voltage operation

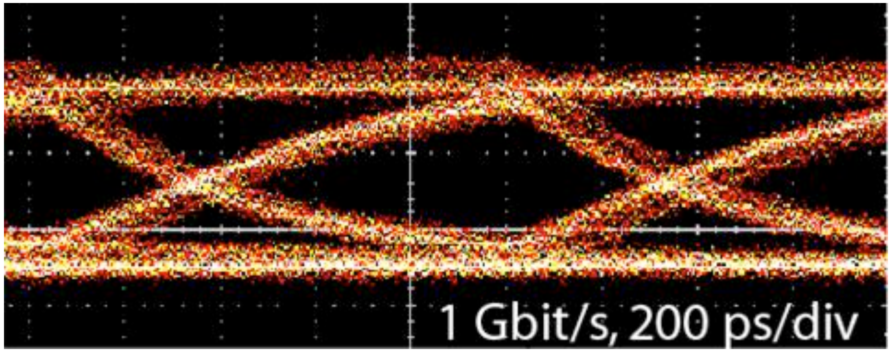




S.Manipatruni, K.Preston, L.Chen, M.Lipson,
" Ultra Low Drive Voltage, Ultra Small Silicon Electro-optic Modulator", Optics Express 2010

Ultra Low Voltage Silicon Micro-ring Modulator





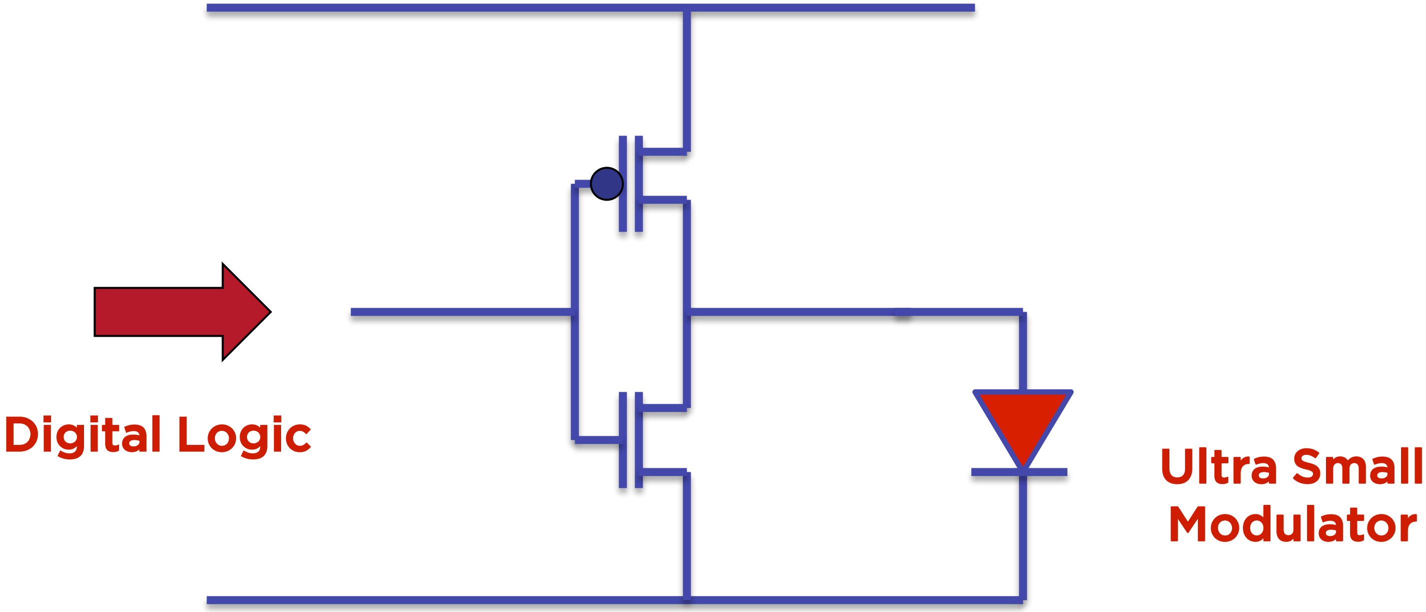
Applied Electrical Signal **Optical Modulation**

1 Gbit/s Modulation using 150 mV peak-peak voltage swing

Smallest Swing Voltage for silicon electro-optic switching to date

S.Manipatruni, K.Preston, L.Chen, M.Lipson,
" Ultra Low Drive Voltage, Ultra Small Silicon Electro-optic Modulator", Optics Express 2010

Towards Direct Digital Logic Drive

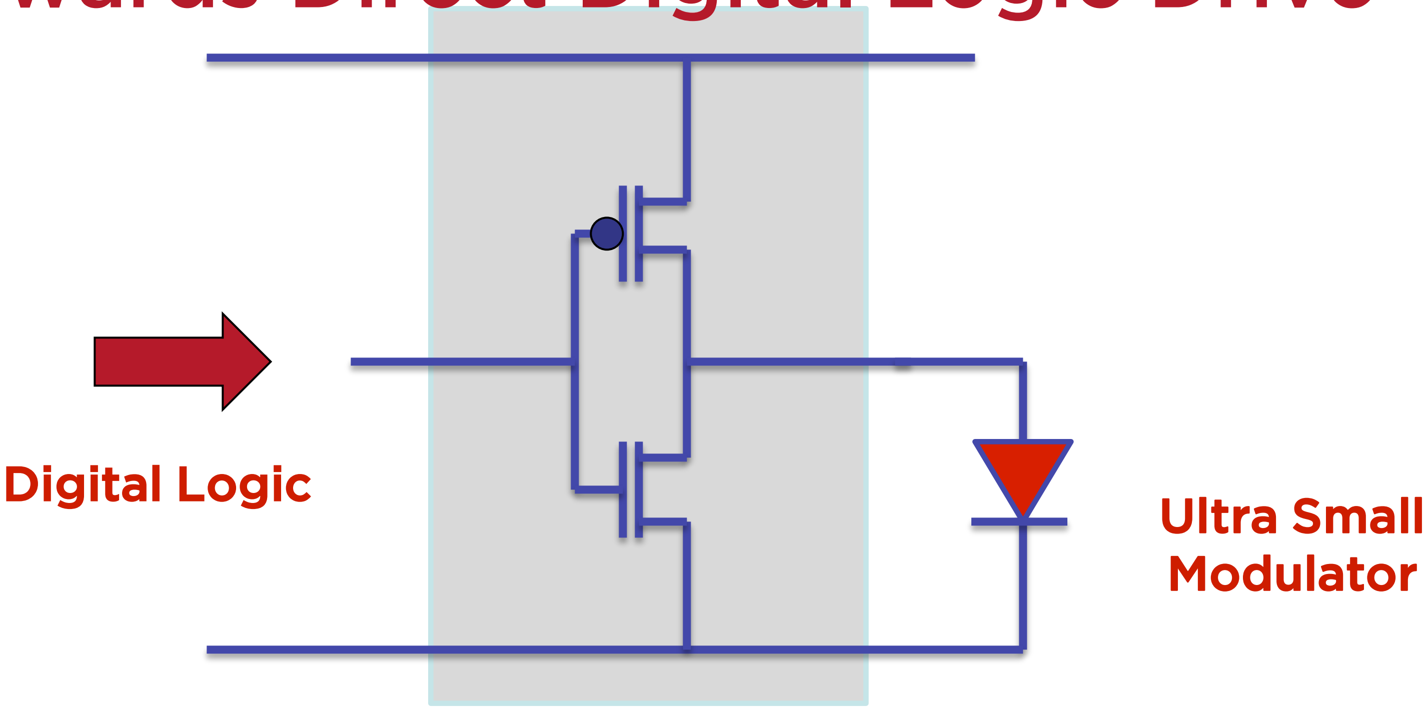


$$t_{sw} = 3\frac{C_n V_n}{I_n} \cdot \frac{I_{modulator}}{I_n} + 1.5 \cdot \frac{C_n V_n}{I_n}$$

http://www.itrs.net/links/2005itrs/Linked%20Files/2005Files/SystemDrivers%20and%20Design/FO4Writeup.pdf

http://www.itrs.net/Links/2009ITRS/2009Chapters_2009Tables/2009Tables_FOCUS_C_ITRS.xls

Towards Direct Digital Logic Drive



$$t_{sw} = 3\frac{C_n V_n}{I_n}.\frac{I_{modulator}}{I_n} + 1.5.\frac{C_n V_n}{I_n}$$

http://www.itrs.net/links/2005itrs/Linked%20Files/2005Files/SystemDrivers%20and%20Design/FO4Writeup.pdf
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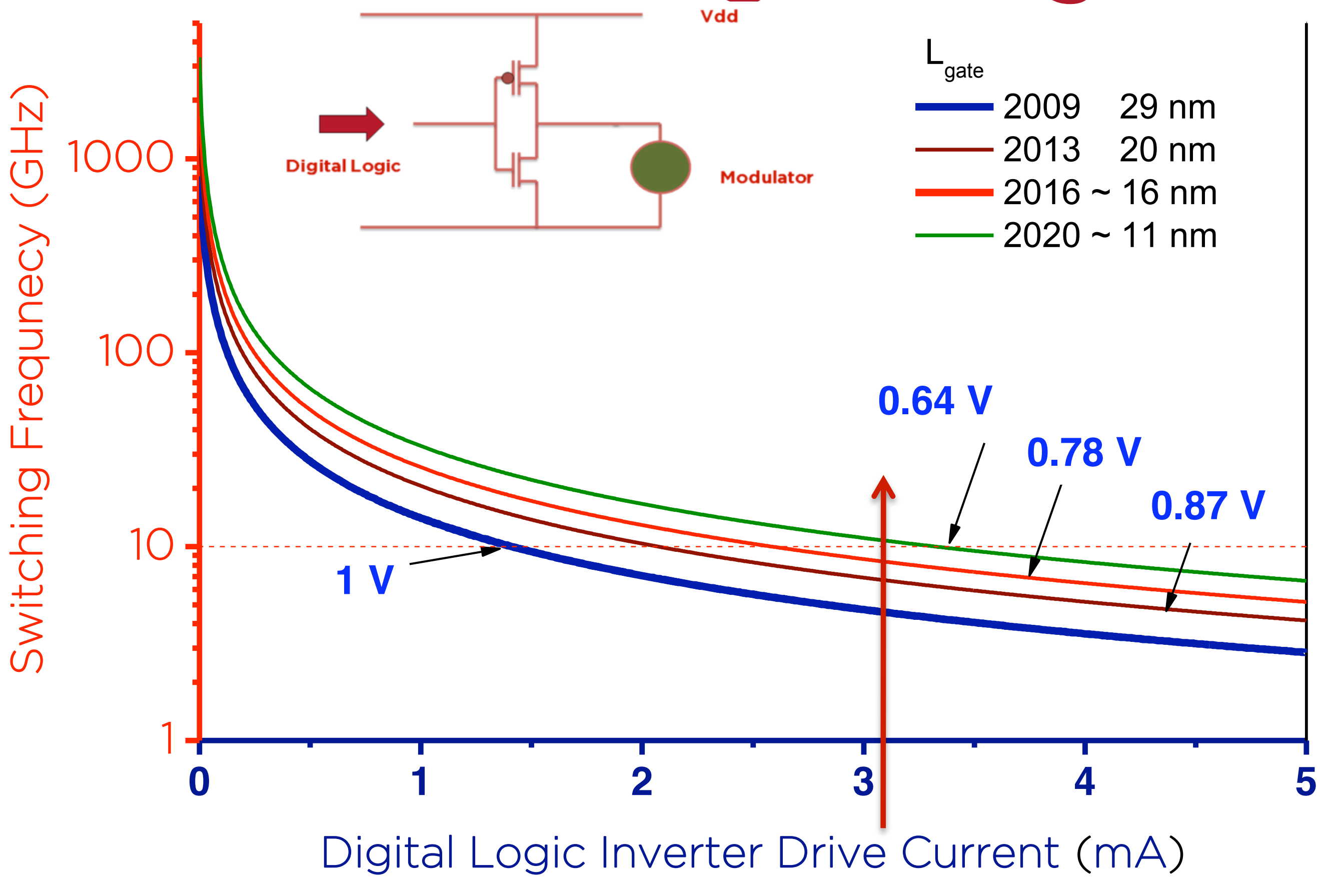
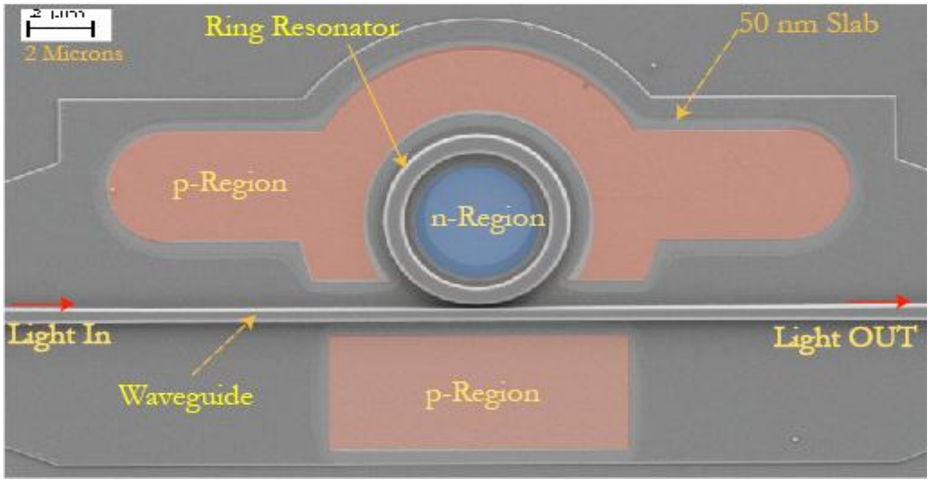
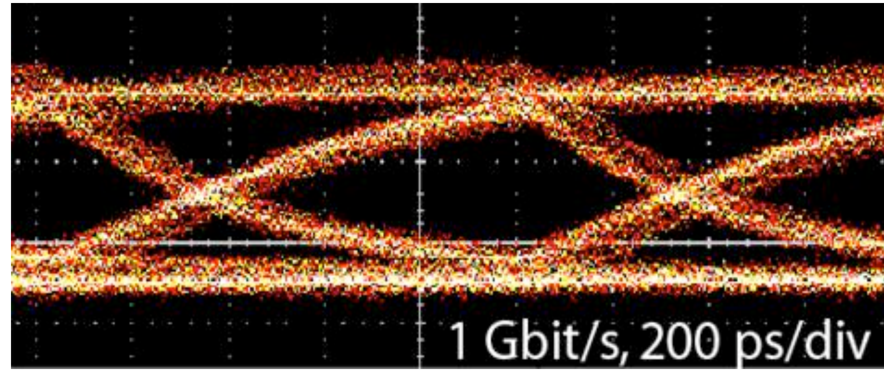
Towards Direct Digital Logic Drive

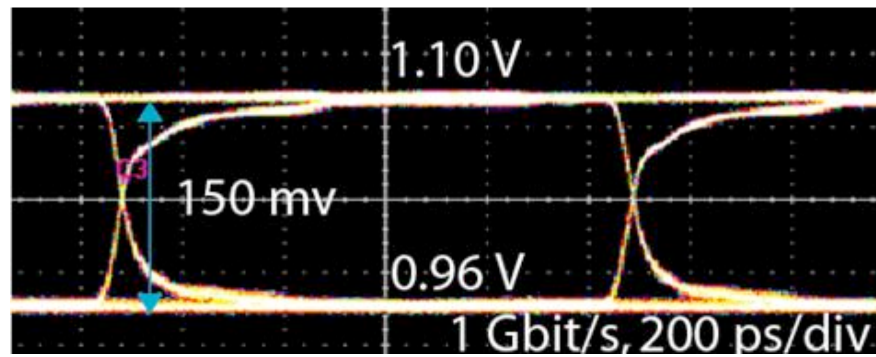


Modulators can be driven with 2 Micron sized transistors at $I_{d,sat}$ of 664 μA/μm

Conclusion



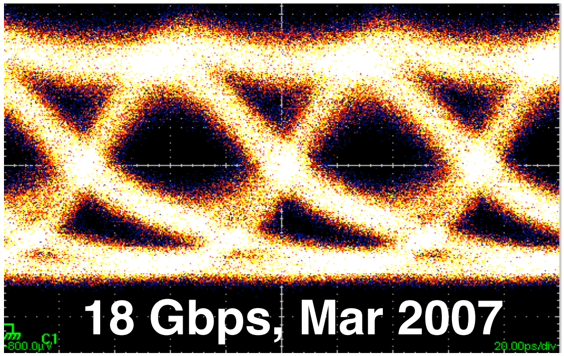




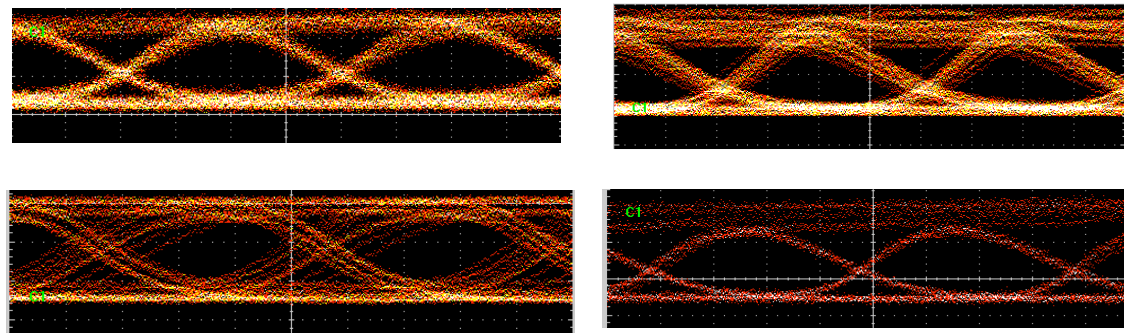
Smallest swing voltage for silicon electro-optic modulation to date

Smallest micro-ring modulator to date

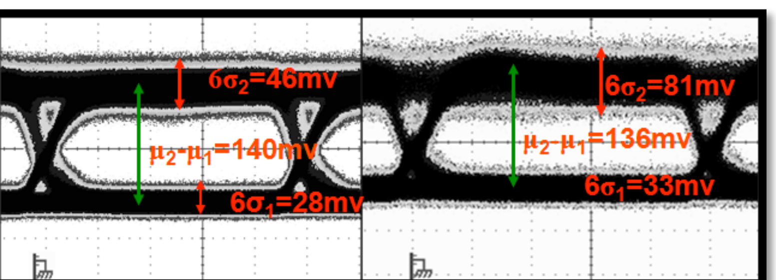
Silicon Electro-optic Modulators:
Building Blocks for Optical Networks on Chip



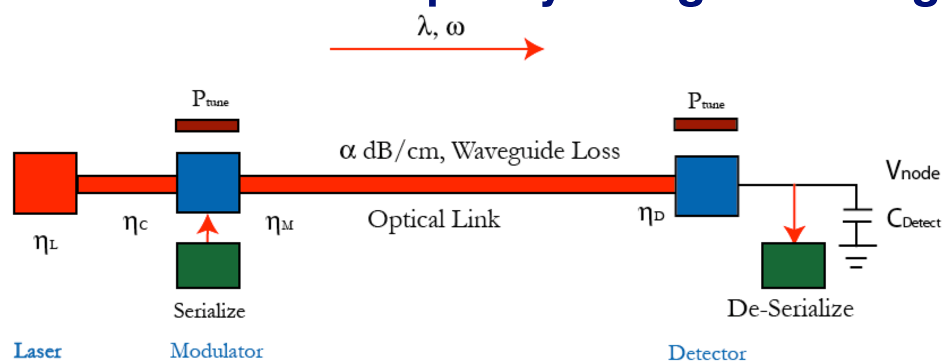
Speed :
Fastest Microring Modulator



Scalability : 50 Gbit/s
Highest Modulation Capacity using microrings



Robustness :
Stability over 15 K



Scaling Rules :
Based on physical models & ITRS

Silicon Nanophotonic Device Requirements

Feature	Description	Target
Link Speed	Operating Speed (B)	> 25 Gbit/s
Clock Speed	System Clock (f_{clock})	5 GHz
Modulator Switching Energy	Switching Energy averaged per bit	10 fJ/bit
Detector	Effective Capacitance & Quantum Efficiency	10 fF, > -1 dB @ 25 Gbit/s
Operating Voltages, Current	Modulator Drive & Detector Out	< 1 V, 1 mA
Waveguide Losses	Single mode waveguide loss	< 1 dB/cm
Coupling Loss	Single Mode Fiber to Single Mode Waveguide Coupling	< 1dB
Laser Quantum Efficiency	Electrical to Optical Conversion	> -3 dB
Serilisation-Deserilaisation	For converting system data to high speed and back	< 20 fJ/bit
Tuning Power	Tuning power for low modal volume devices	250 μW/nm
Operating Range	Transient Tuning Range	20 K run-time

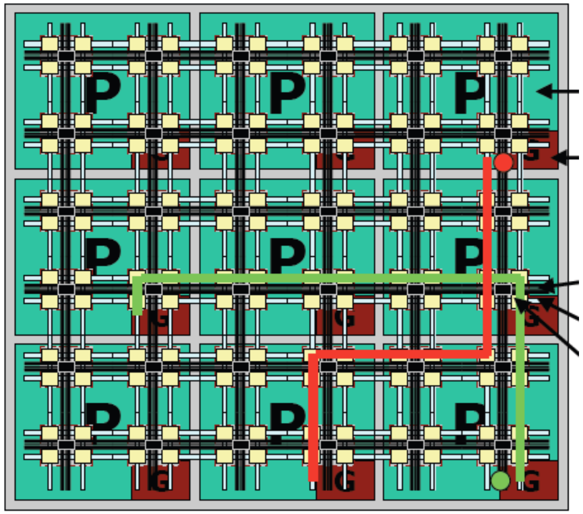
Table 1.3: Device Requirements for sub 100 fJ/bit Silicon Nanophotonic Interconnects*

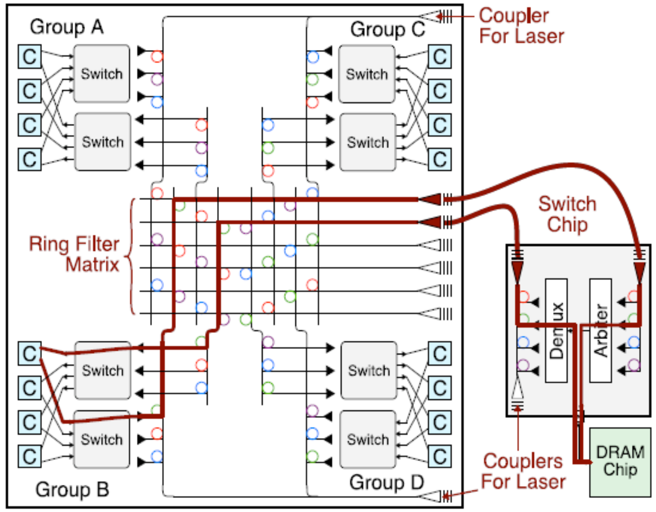
** We provide one possible set of device parameters. A large range of devices can meet the requirement with appropriate tradeoffs.*

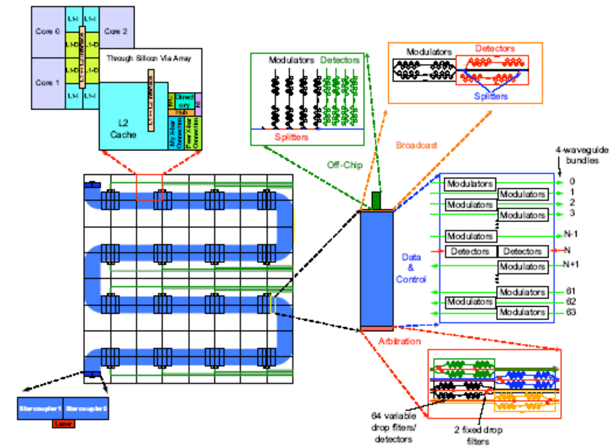
Compact, Multi-wavelength, High speed, CMOS Silicon Photonic Components

Property	Description	FOM Target
Compact	Size of modulators, detectors, switches	D > 500 Tbps/mm^2 Modal Volume ~ 1 μm^3 Detector C_d< 10 fF, QE> 80%
High Speed	Data rate per channel	f~ 10-40 Gbps
Multi-wavelength	Multiple wavelength networks	Interconnect Density (D) > 50 Gbps/ µm
CMOS compatible	Low voltage, low current, Low Temperature	Vdd, Id < 600 mV, 1 mA

Silicon Photonics Impact So Far : Computing







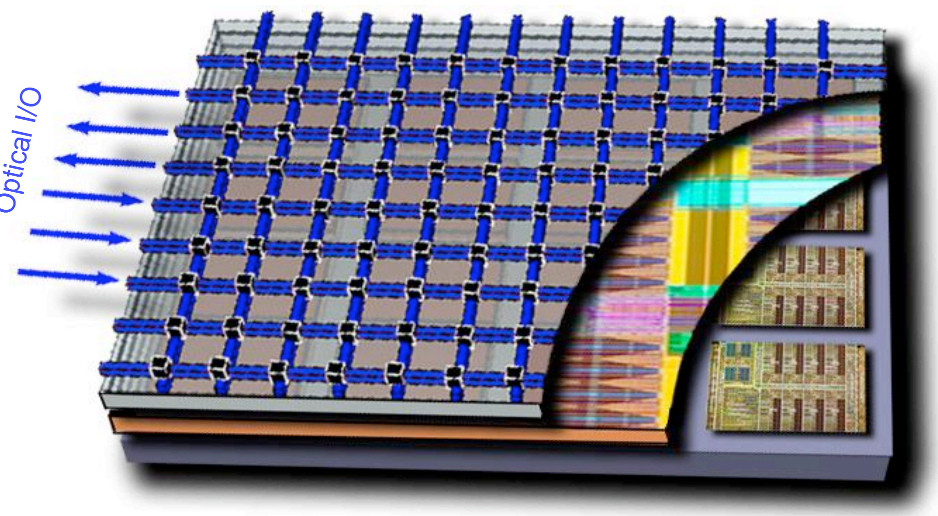
Columbia, IBM
Bergman, Kash et al

C. Batten et al

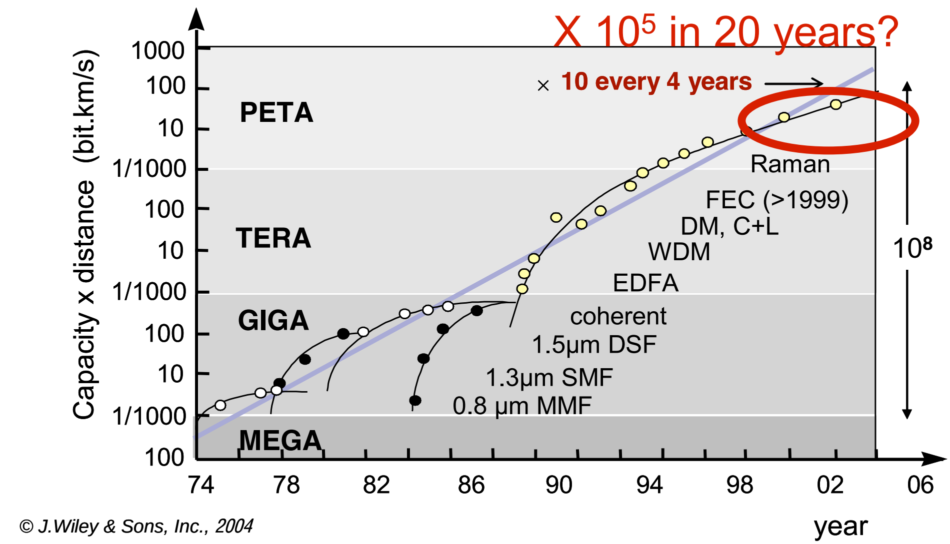
Sun, HP Labs
A. Krishnamoorthy, Beausolil et al

Most proposed multi-core network architectures are based on Silicon photonic building blocks.

Nanophotonics: Opportunities



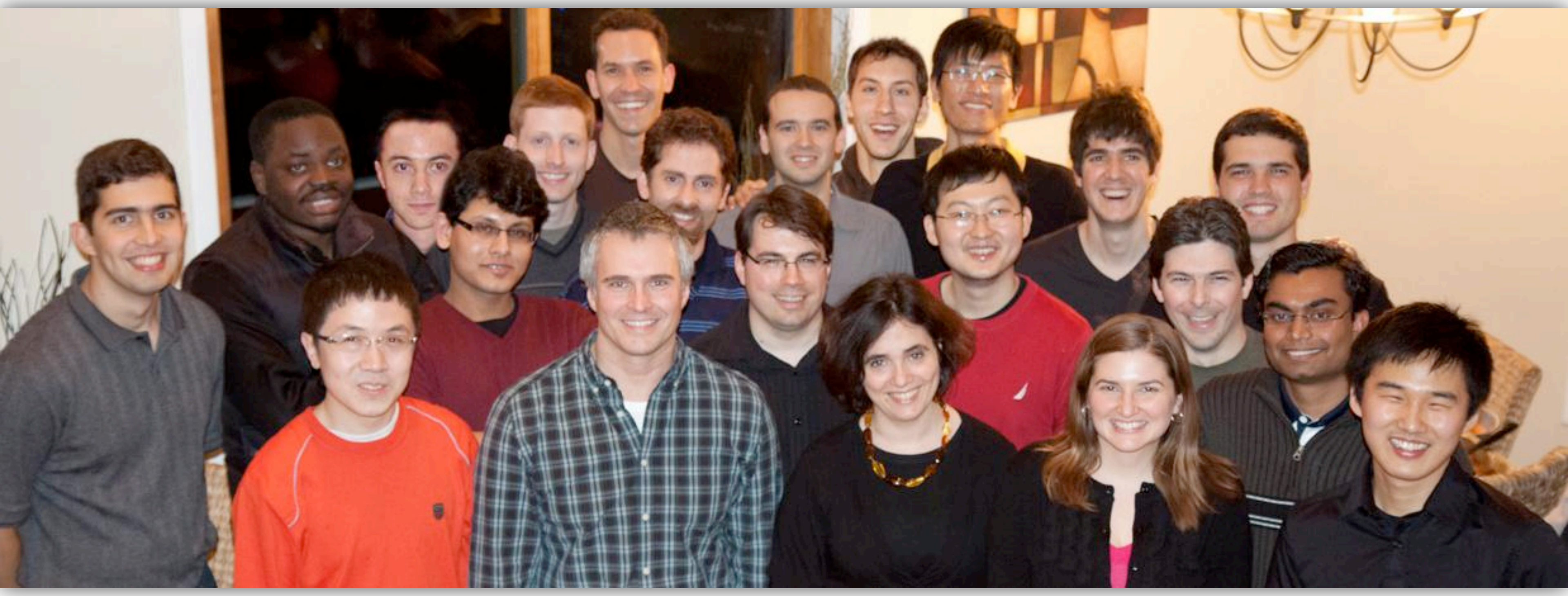
High Performance Computing



Evolution of telecommunications; E. Desurvire, 2006

Scalable Devices for Web 3.0

Acknowledgements



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