Silicon Photonics: Optical Connectivity at 25 Gbps and Beyond.

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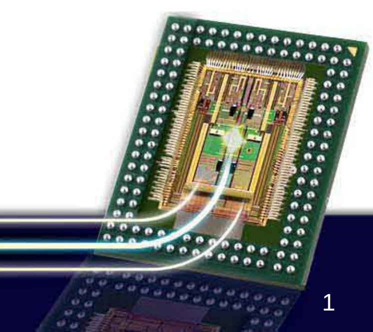
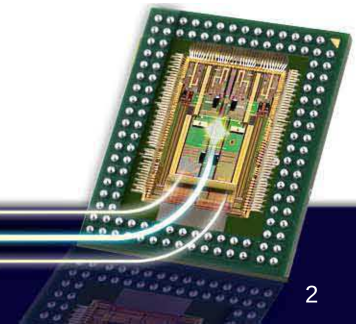
Company: Luxtera



Outline

- **Motivation**
  - Limitations of conventional solutions
  - CMOS photonics advantages
- **CMOS photonics technology overview**
- **Light Sources for CMOS Photonics**
- **CMOS Photonics Transmitter**
- **CMOS Photonics Receiver**
- **Optical Transmission Channel**
- **Future technology direction**
- **Conclusion**

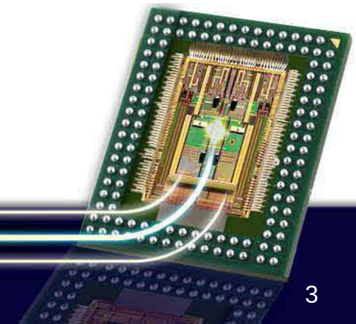


Motivation

- **Interconnect quickly moving beyond 10Gbps per lane**
  - 16G Fibre Channel : 1x14 Gbps
  - FDR Infiniband : 4x14 Gbps
  - EDR Infiniband : 4x25 Gbps
  - 100G Ethernet : 10x10Gbps → 4x25 Gbps
  - 32G Fibre Channel : 1x28 Gbps

- **Reach of copper decreases rapidly with faster data rates**
  - Driving the need for lower cost optical interconnect

- **More system ports require optical interconnects**
  - Higher proportion of system cost and power going to interconnect
  - Interconnect limitations can impair interconnect fabric roadmap
    - Move to parallel vs. serial solutions



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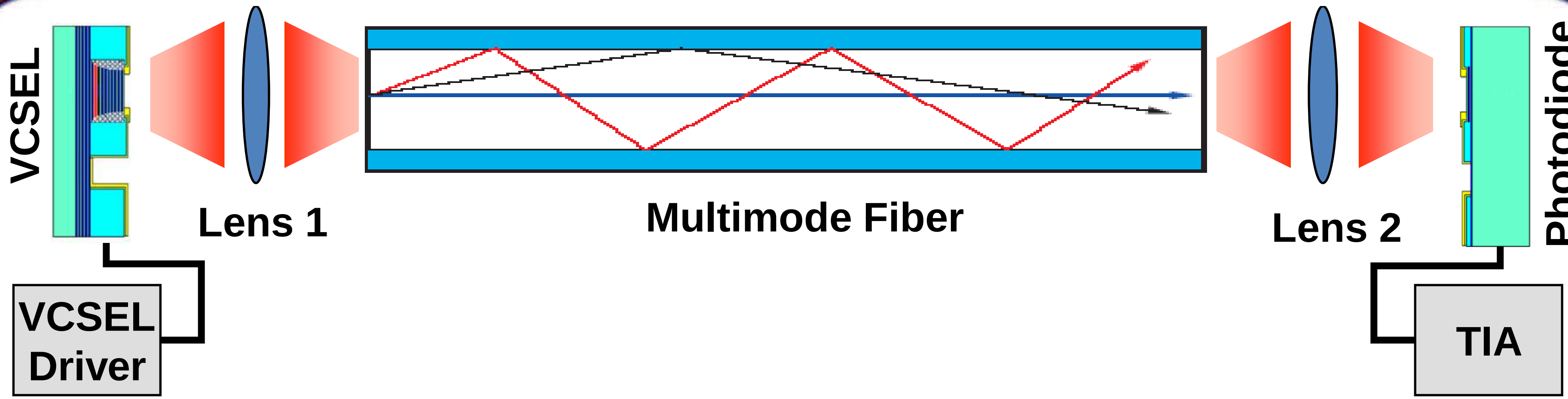
VCSEL Challenges with Scaling Beyond 14G



VCSEL Transmitter

- VCSELs need to be driven with high bias currents in order to operate at high speeds. Reduced diameter also required.
- Results in high current density and hence reduced VCSEL reliability and manufacturability.

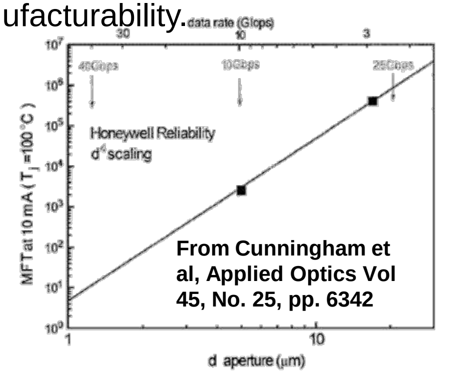
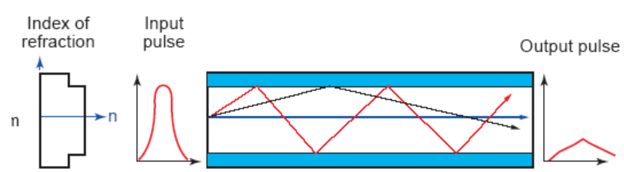


Fig. 4. Scaling of the MTTF versus aperture for Honeywell VCSELS.

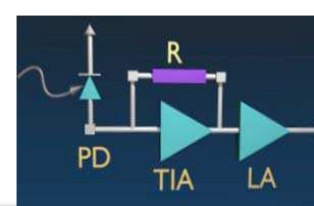
Multimode Fiber Medium

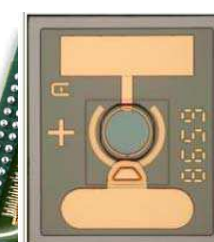
- Modal and chromatic dispersion limit bandwidth.
- OM3 fiber has a bandwidth length product of ~2000 MHz*km under optimum coupling conditions.
- Chromatic dispersion is dealt with by stringent specs on laser spectral line width (lower yield).



Multimode Receiver

- Multimode fiber receivers require large area photo-detectors (60-70 micron diameter), capacitance is in the order of 240 fF.
- Receiver bandwidth determined by RC time constant of PD/TIA. Reducing R is a possibility but that reduces the gain (receiver sensitivity).





CMOS Photonics Technology Summary

Basic Technology:

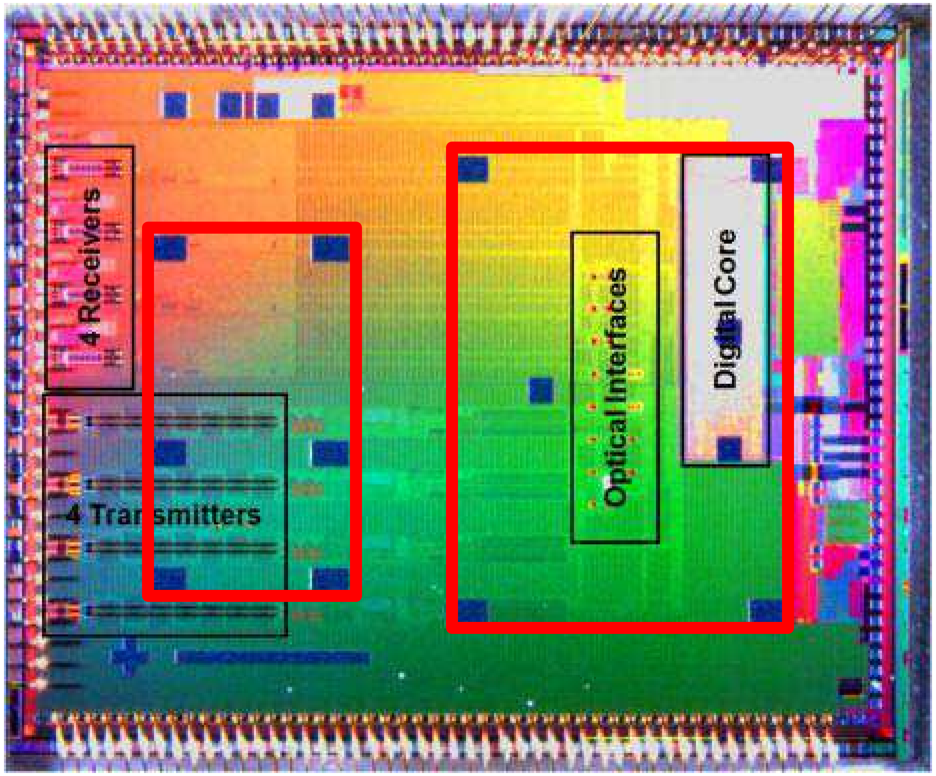
- Integration of photonic and electronic functions on one die (low cost)
- Manufactured using standard tools in a mainstream CMOS fab

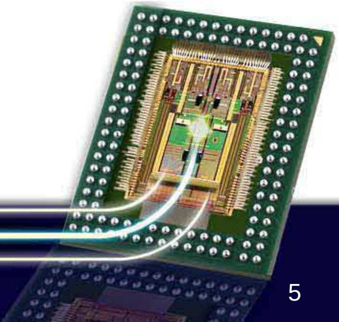
Lux-G process:

- Based on Freescale Semiconductor 130 nm SOI CMOS node
- Reliability qualified per JEDEC 001
- Currently in full manufacturing mode (maturity level 3)

Integrated functions on CMOS die:

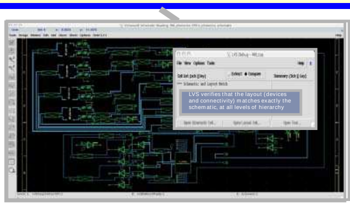
- Electronic circuits
- Passive and active waveguide devices
- Coupling structures
- Photo-detectors



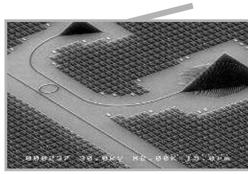


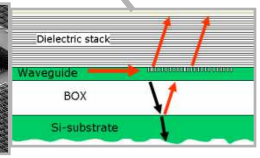
CMOS Photonics Ecosystem

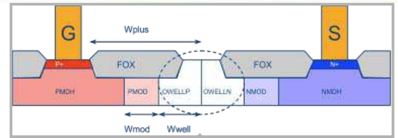
Automated design infrastructure:
- extensive photonics device library
- full electronic-photonic DRC & LVS
- circuit & system simulation



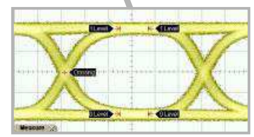
Photonic structures on custom SOI wafer by standard CMOS processes: waveguides, couplers



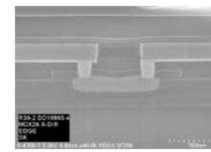




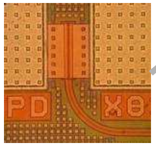
Doping for EO structures:
- high speed modulators
- phase shifters
- VOA



Standard CMOS gate process



Selective growth of Germanium islands for photo-detectors



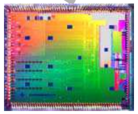
Standard CMOS metal interconnects & vias

Standard CMOS Passivation & End Metal

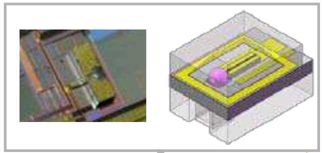
Complete Ecosystem from chip design to finished product

Fully automated wafer level photonic and electrical probing

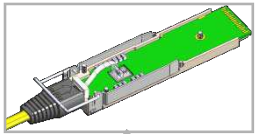
Die Singulation



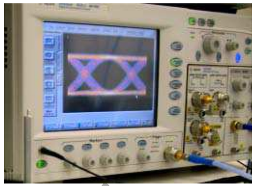
Automated Laser Attach



Packaging & Automated Fiber array Attach



Automated Test



PRODUCT

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Light Source for CMOS Photonics

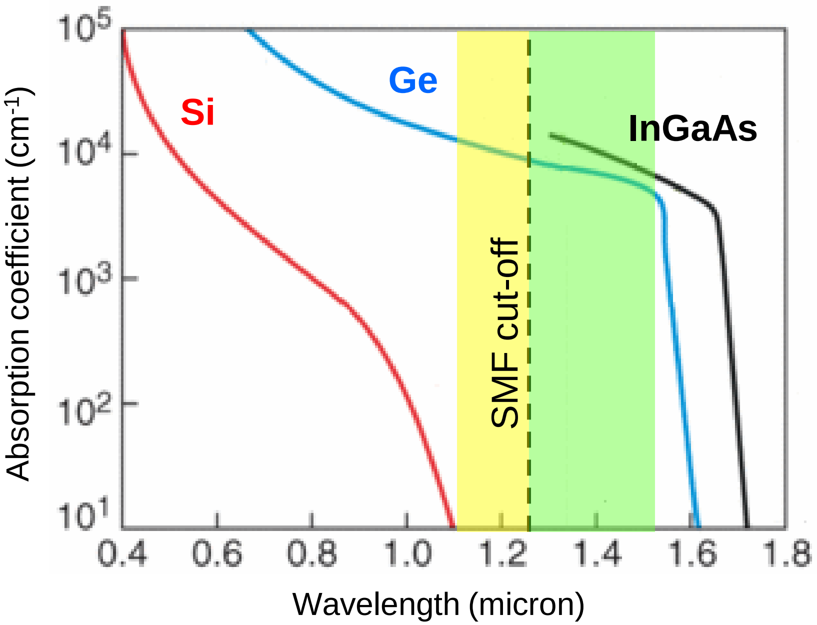
Light source operates CW

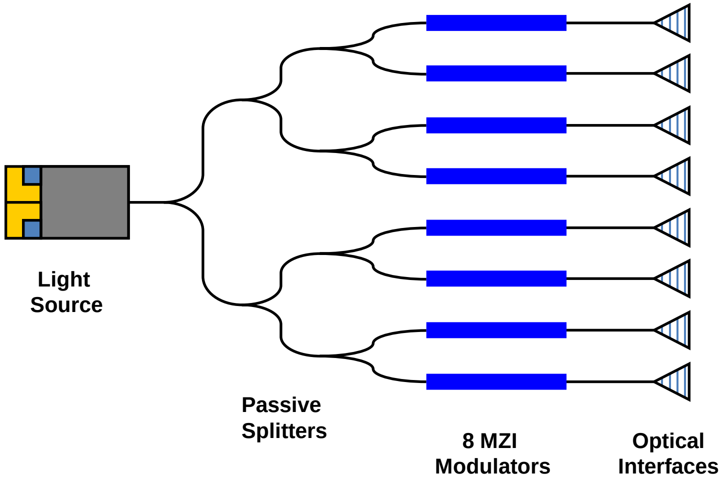
Single laser for multiple channels
- Cost reduction
- Power reduction
- Improved reliability
- Presently up to 150 Gbps of throughput per laser
  - Moving to 300+ Gbps of throughput per laser

Silicon photonics solutions can be implemented from 1260nm to 1570 nm.

MQW DFB laser diodes
- Current wavelength 1490 nm
- Manufactured in volume by several vendors (FTTH)
- DFB lasers have very good reliability track record (very low random and wear-out failure rate, both < 1 FIT)

Laser diode packaged in hermetic silicon housing
- High reliability
- Waferscale Manufacturing

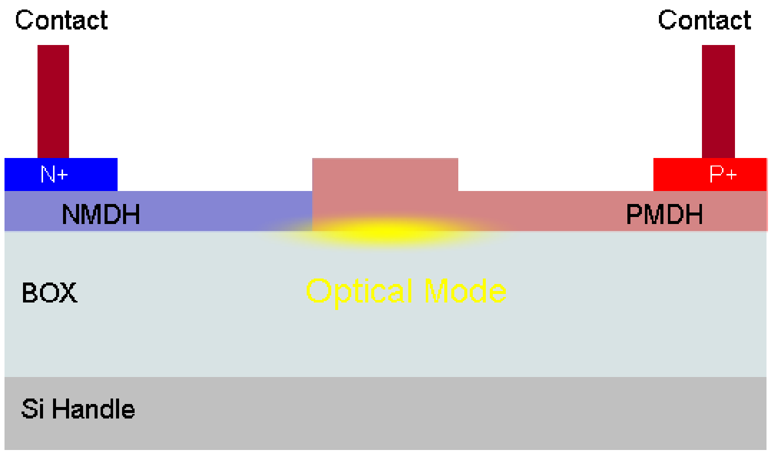




Transmitter - Photonics

Basic high-speed phase modulator

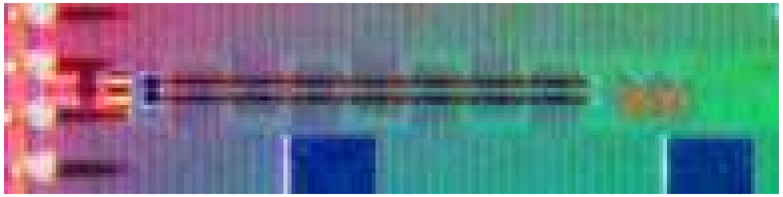
- Based on carrier depletion
- Reverse-biased lateral pn junction provides high-speed phase modulation
- Theoretical speed limited by:
  - Relaxation time (= $\varepsilon*\sigma$ = 12.3*8.6* 10^{-14} F/cm*1 Ω.cm = 1 ps)
  - **<u>Bandwidth = 160 GHz</u>**
- Voltage swing: 0 to 2 V reverse bias



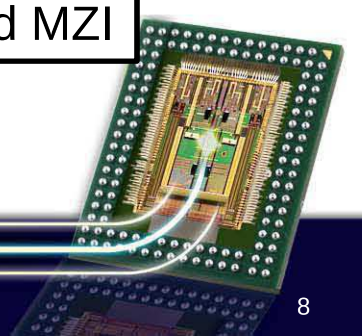
High Speed Phase Modulator

Distributed Mach Zender Interferometer enables better Opto-Electric phase matching

- Enables waveform shaping to center peak OMA at 0.5 UI
- Enables transmitter power reduction



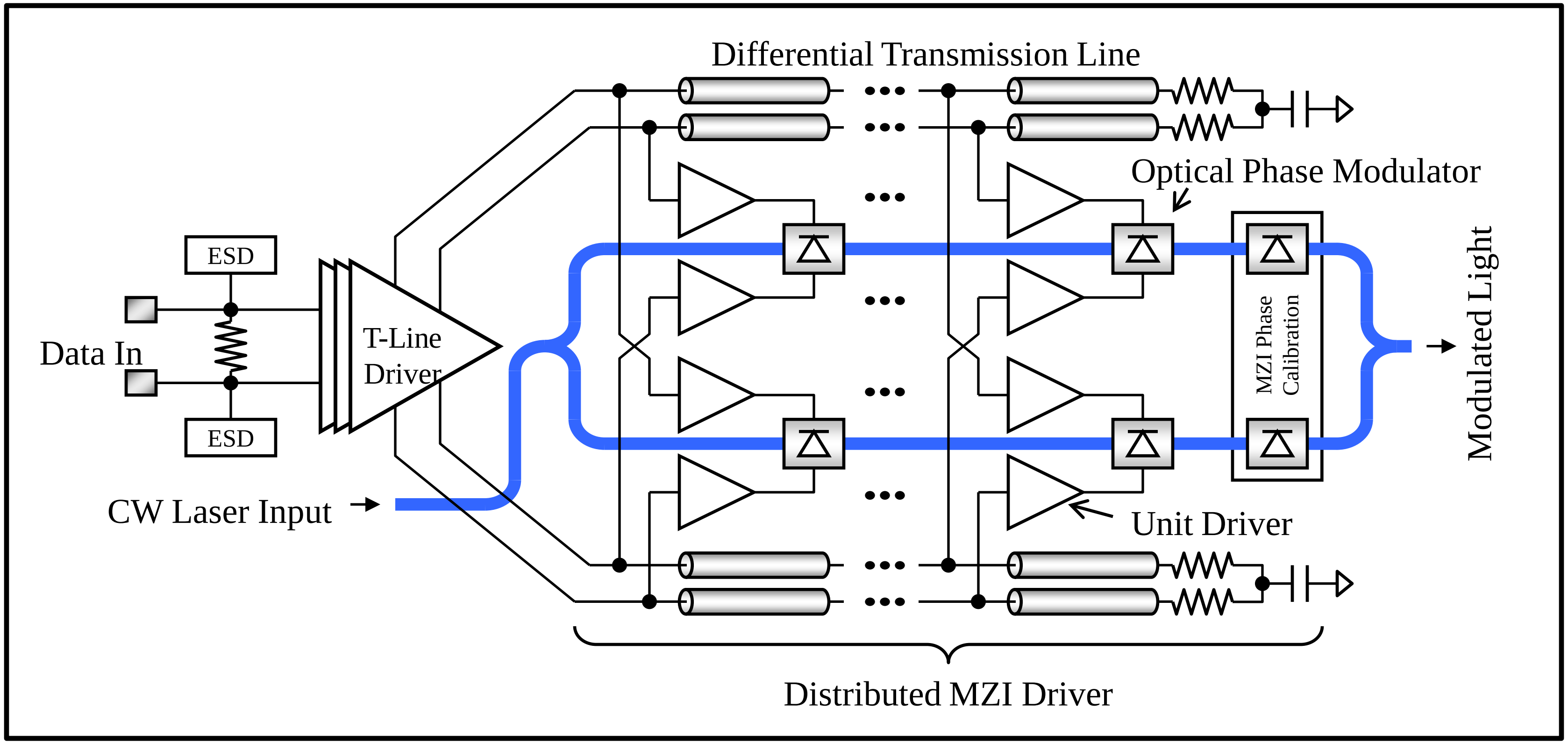
Distributed MZI



Transmitter - Electronics

Stacked domain design
- Enables high speed, low voltage CMOS to be used.
- Discrete solutions require high voltage drive capabilities (SiGe).

Distributed electrical driver
- Minimizes parasitics between electronics and optics.
- Discrete solutions require wire bond or flip-chip interconnects.



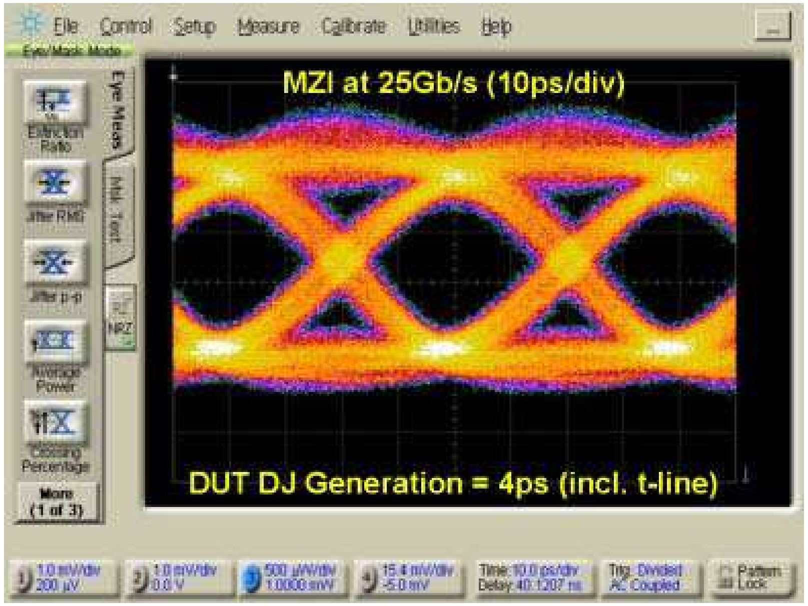
Transmitter – Experimental Results

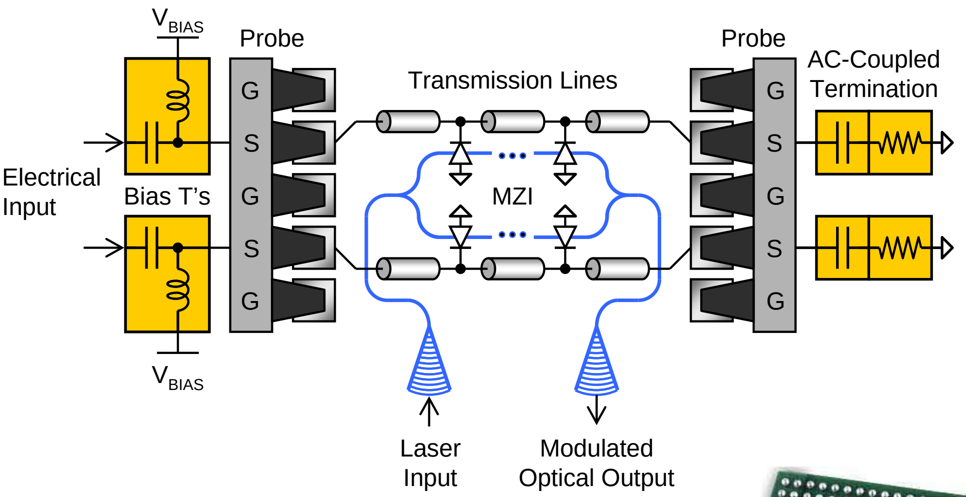
Tested 2 mm long MZI

- Existing, discrete test structures not optimized for high speed performance

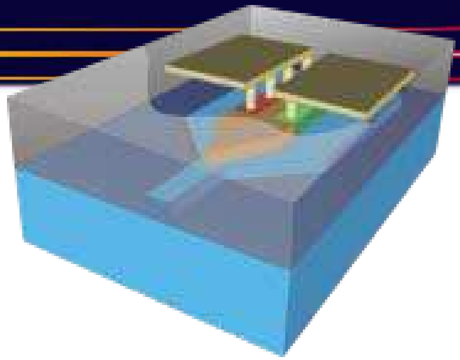
Straightforward optimization for 4 x 25 Gbps and higher

- MZI Deterministic jitter generation < 4 ps
- Implementation within distributed MZI would reduce yield DJ < 2ps





Receiver - Photonics



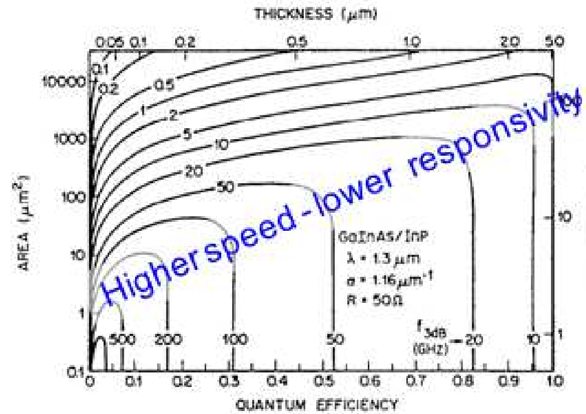
Conventional surface illuminated photodiodes, design trade-off :
- Increase bandwidth by reducing transit-time (reduce thickness of depletion region)
- Increase bandwidth by reducing capacitance (reduce surface area)

Waveguide photo-detectors, design trade-off broken:
- Absorption and collection occur along perpendicular directions
- Speed and responsivity can be independently optimized

Theoretical bandwidth of waveguide photo-detector
- Transit-time limited bandwidth, due to very small junction area and hence negligible junction capacitance
- Transit time governing equation
  (d=depletion thickness, V = applied voltage, u = free carrier mobility)

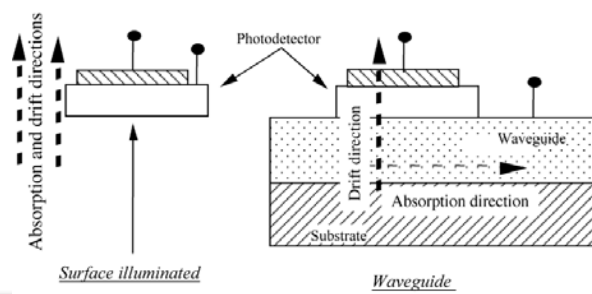
$$t_t = \frac{d^2}{V\mu}$$

- Existing design, **Bandwidth = 55 GHz**



Contours of constant 3-dB bandwidth in the detector-area, depletion-layer-thickness plane. ($\alpha = 1.16\ \mu m^{-1}$, (1.3-μm wavelength), $v_n = 6.5 \times 10^6$ cm/s, $v_p = 4.8 \times 10^6$ cm/s, $\epsilon = 14.1$.)

(Bowers1987)

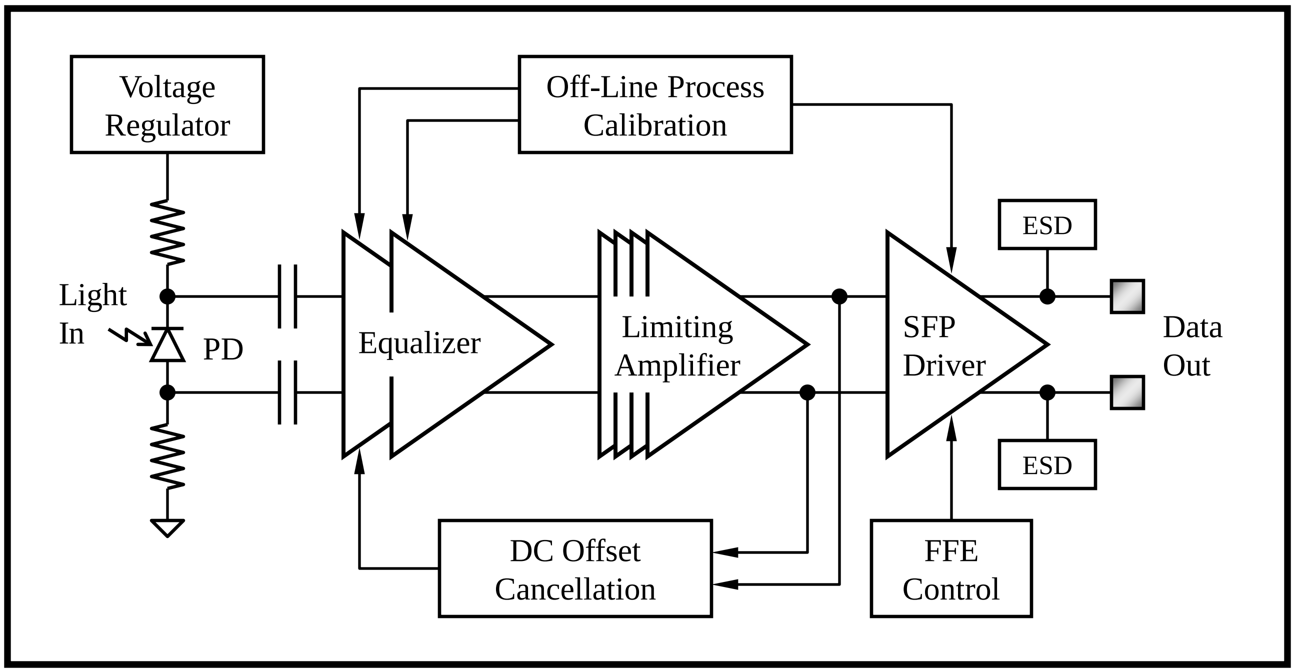


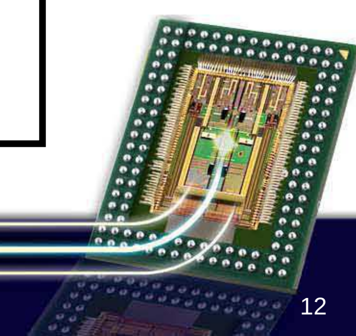
Receiver - Electronics

Completely monolithic (integrated photo-detector, regulator, amplifiers, and control/calibration functions)

– Very low photodiode and parasitic capacitance at PD/TIA node enables very high gain receiver front end → <u>Very high sensitivity</u>

– Integrated solution enables very low jitter compared to discrete solutions





Receiver – Experimental Results (Preliminary)

CMOS process technology:

- Selective Ge epitaxy on Si
- Standard CMOS foundry toolset for Ge epitaxy (SiGe stressors, HBT)

Ge PIN Photo-detector

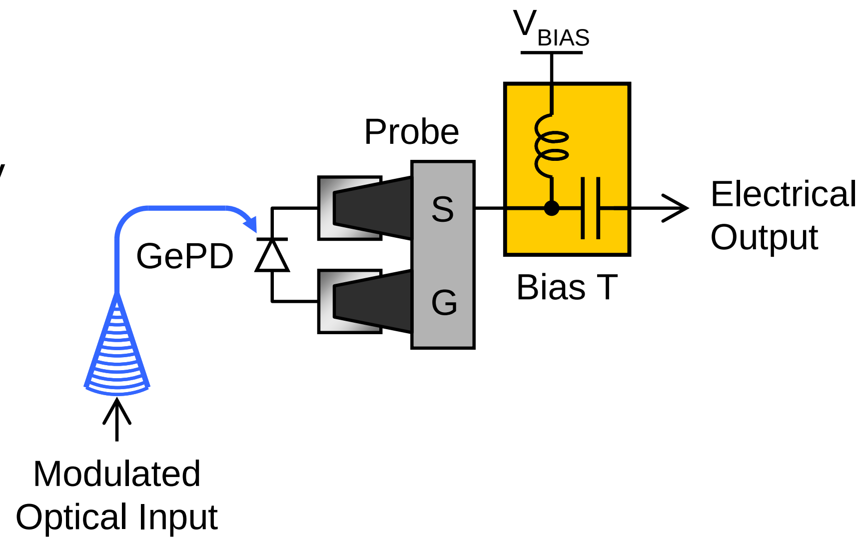
- Responsivity > 0.85A/W @1490nm
- Capacitance < 15fF @ -1.2V
- Demonstrated operation at 25 Gb/s (without optimization)

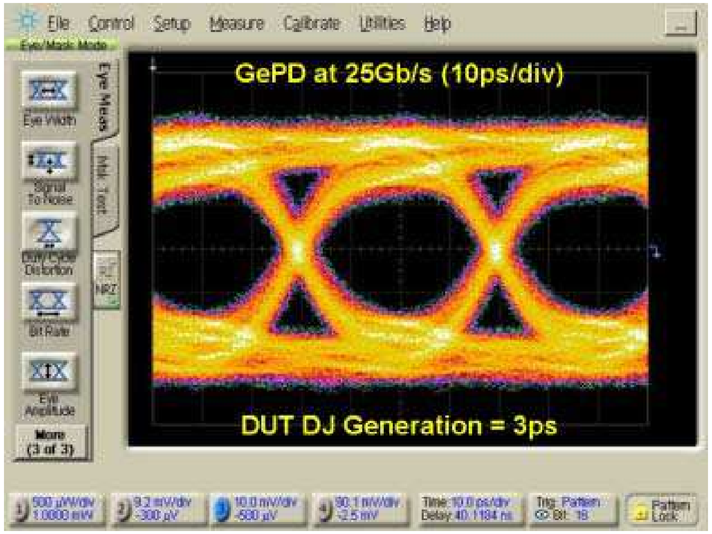
Reliability:

- PIN qualified per Telcordia GR-486-CORE

System performance:

- Low capacitance allows much higher sensitivity than discrete solutions (~4 dB)



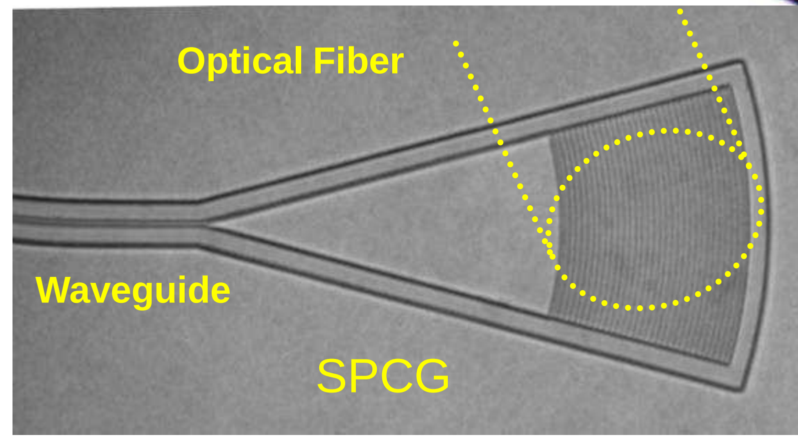


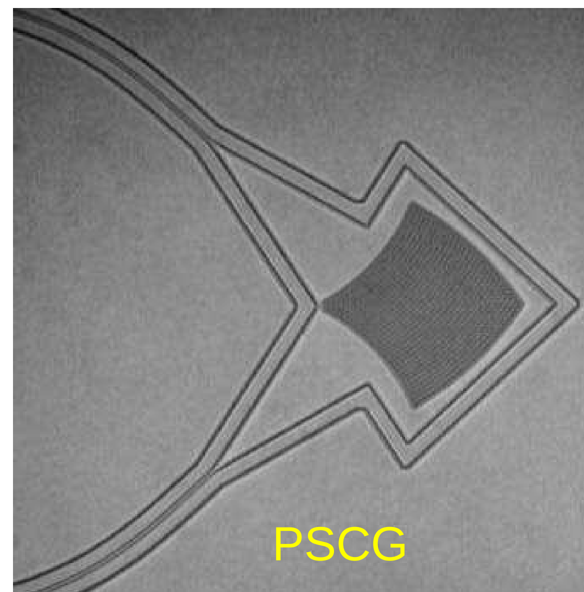
Optical Transmission Channel - Overview

Transmitter path:
- Single polarization grating couplers
- CMOS photonics waveguides & splitters combiners
- Mach-Zehnder interferometer
- Low-speed monitor photodiodes

Interconnect medium:
- Broadband single mode fiber

Receiver path:
- Polarization splitting grating coupler
- CMOS photonics waveguides
- High speed photodiodes





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Optical Transmission Channel - Characteristics

Grating Couplers

– No discernible data rate dependence

Waveguides & splitters/combiners

– On chip trace lengths a few cm long

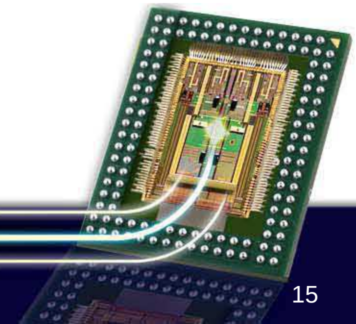
– Dispersion effects significant only above 100m in length

- Optical attenuation stronger factor than dispersion

Single mode fiber

– Dispersion effects become evident at several km in length

– Negligible dispersion in short reach interconnects



Future Potential Applications

- **Single Channel Solutions:**
  - 16G Fibre Channel
  - 32G Fibre Channel
  - 40G Serial Ethernet?
- **4 Channel Solutions:**
  - 4x14G FDR InfiniBand
  - 4x25G EDR InfiniBand
  - 4x25G 100G Ethernet
  - 4x32G Fibre Channel Switch to Switch
- **12+ Channel Solutions:**
  - 12x25G EDR InfiniBand
  - 16x25G 400G Ethernet?
- **Embedded Solutions:**
  - 4/12/16 x 25G MCM mountable solutions
  - Optical backplane interconnects
- **3D Video Interconnects**

Conclusions

CMOS Photonics is capable of serial data rates well beyond 25Gbps

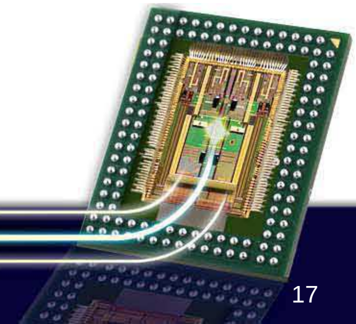
- Theoretical modulation limit of 320 Gbps
- Theoretical detection limit of 110 Gbps (with current photodiode depletion thickness)

CMOS Photonics rate capability directly correlated to host systems capability

- Removes the possibility of interconnect being the limiting factor for new systems development for the foreseeable future.

CMOS photonics reaches reliability levels host system designers have grown to expect based on copper channels

- Reliability limited by light source, which has a FIT < 1.



Acknowledgements

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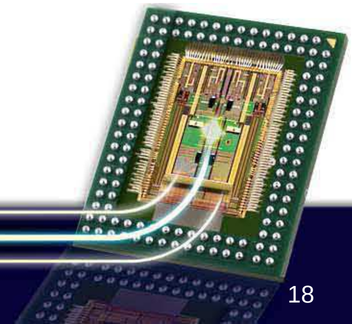

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