40Gb/s Optical Active Cable Using Monolithic Transceivers Implemented in Silicon Photonics Enabled 0.13-µm SOI CMOS Technology

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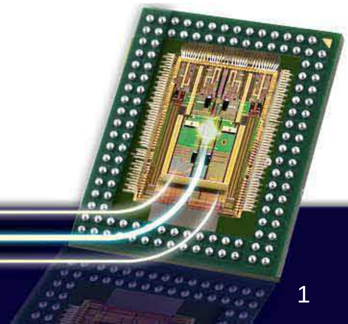
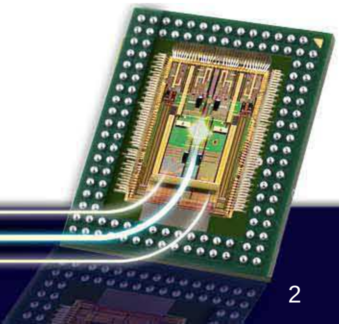
Contributors: Luxtera Team



Outline

- Motivation
  - Data center challenges
  - Active cable advantages
- 40Gb/s optical active cable overview
- CMOS photonics technology overview
- Integrated optoelectronic transceiver IC
- Receiver architecture
- Transmitter architecture
- Measurement results
- Conclusions



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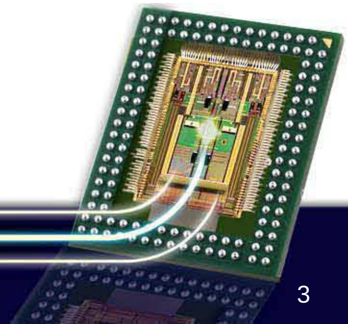
Motivation

- Electric power used to run and cool data centers can account for over 40% of their total cost
- According to 2006 EPA study 1.5% of total energy consumption in USA can be attributed to data centers
  – That's $4.5B
  – Current trends predict that power consumption will approximately double by 2011
  – Energy costs keep increasing as well
- Number of servers increases linearly, but storage capacity increases at an even faster rate
- Data center consolidation and use of space-efficient blade servers increase power consumption per sq-ft, creating cooling challenges, which demand even more power to address
- **Energy-efficient connectivity is part of a solution…**



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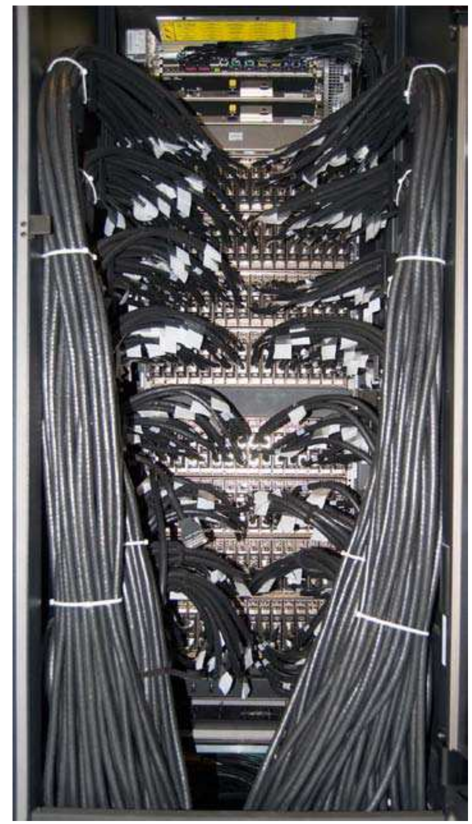
Data Center Connectivity

- Optical active cables offer better form factor and performance
  - Allow fully-populated racks, and larger, distributed clusters with better air flow and cooling
  - 4km reach
  - Low power
  - Light weight
  - Small diameter
  - Easily routed
  - Low EMI
  - No ground loops

Optical Active Cables



Copper Cables

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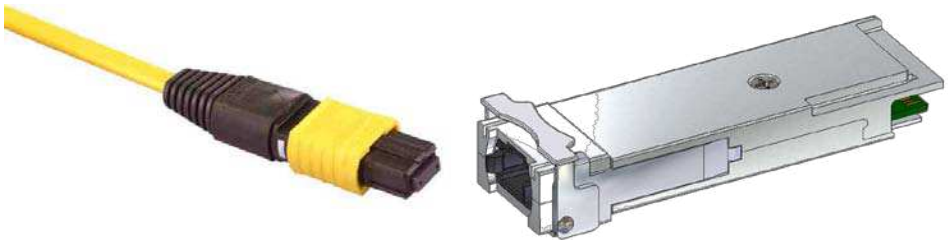
Why Use an Active Cable?

Traditional Pluggable QSFP Module



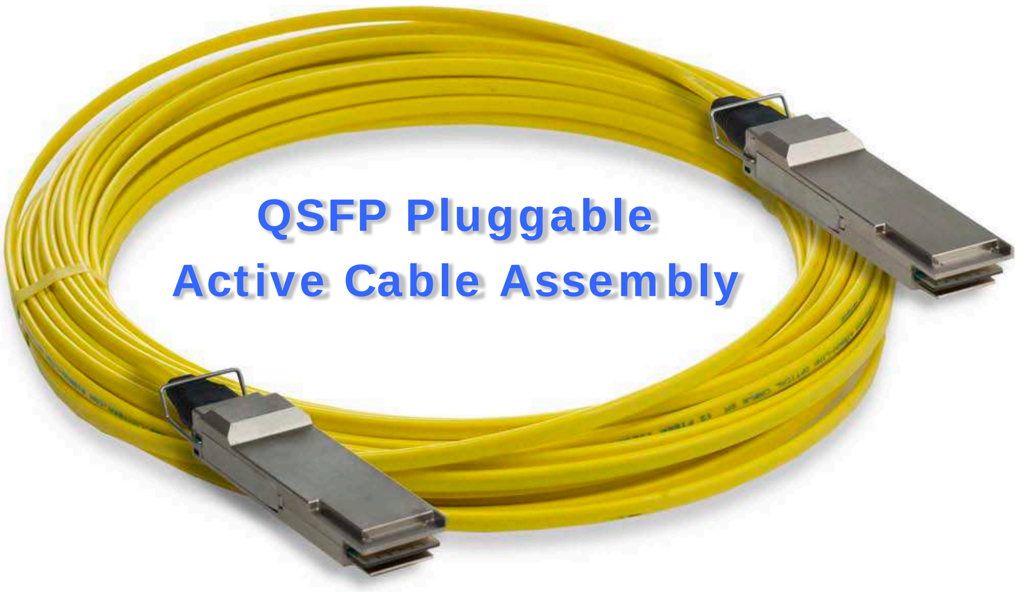
- **Optical connector adds cost due to:**
  - Connector and receptacle cost
  - Fiber polishing cost
  - Light loss at connector
  - Extended dynamic range due to multi-vendor interoperability
- **Optical connector handling issues**
  - Susceptible to scratching
  - Susceptible to dust and moisture
  - Difficult to clean in case of contamination

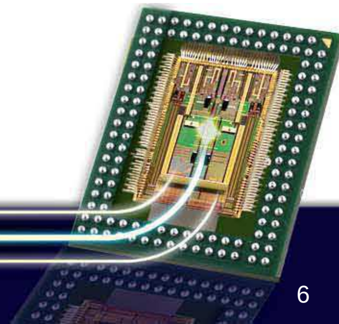
QSFP Pluggable Active Cable

- **Integrated solution advantages:**
  - Cuts cost by attaching fiber directly to the chip
  - No field connector attachment and fiber polishing required
  - Utilizes lower cost lasers, no light loss at the connector
  - Closed cable system eliminates multi-vendor interoperability concerns
- **Rugged mechanical solution**
  - Handles like copper cable
  - Hermetically closed optical system eliminates environmental concerns

40Gb/s Optical Active Cable Overview

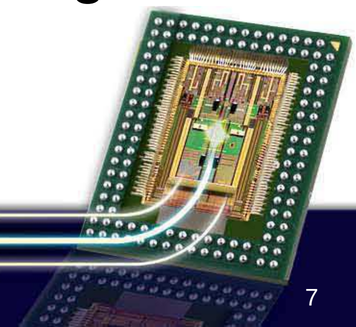
- Four-lane, full duplex, multi-rate transceiver
  - 1Gb/s to 10.52Gb/s per channel
  - Total cable bandwidth 42Gb/s
  - Power consumption significantly lower than 1W per end
  - BER $< 10^{-15}$
- Available at multiple lengths up to 4km
- QSFP+ MSA form factor compatible
- SFP+ compliant electrical interface
- Supports InfiniBand, 40G Ethernet, Fibre Channel, and proprietary applications
- Single-mode ribbon fiber
  - Fiber coupled directly to the die
  - Permanently attached to transceivers
- Hot pluggable and field replaceable
- Bend Radius of 5mm
- Cable pulling strength of 50lb





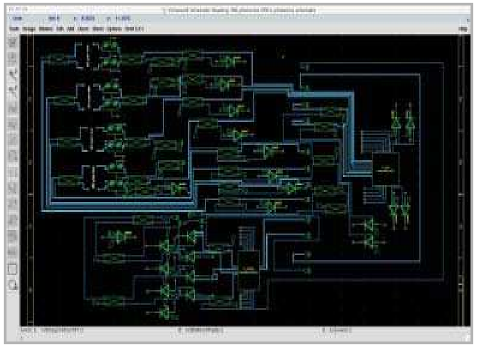
CMOS Photonics Technology Highlights

- Very dense photonic waveguide routing
- Seamless integration of electronics and optics
- Monolithic integration of high speed photo-detectors
- Increased receiver sensitivity
  - Extremely low detector capacitance
- Wafer scale OE functionality testing
  - Vertical light couplers → optical “pads”
- Sharing single laser source for multiple channels
  - CW laser → optical “power supply”
- Fewer parts by integrating analog and digital electronic functionalities on a single die
- Leverages CMOS infrastructure for low cost and high volume manufacturing

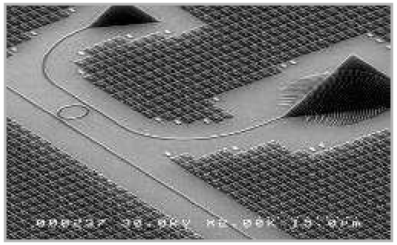


CMOS Photonics Technology Summary

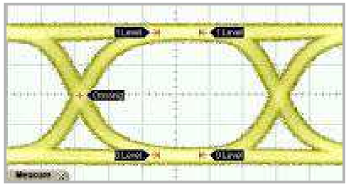
Automated design infrastructure:
- extensive photonics device library
- full electronic-photonic DRC & LVS
- circuit & system simulation

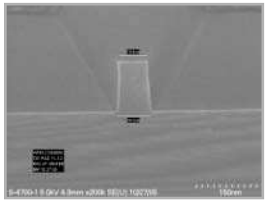


Photonic structures on custom SOI wafer by standard CMOS processes: waveguides, couplers



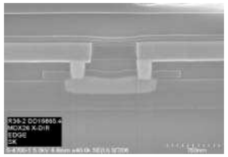
Doping for EO structures:
- high speed modulators
- phase shifters
- VOA



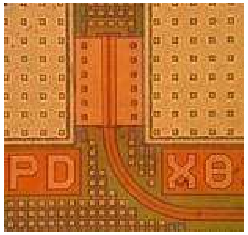


Standard CMOS gate process

Selective growth of Germanium islands for photo-detectors



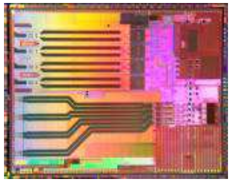
Standard CMOS metal interconnects & vias



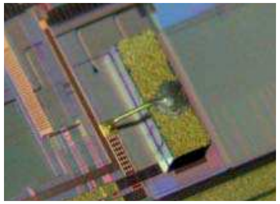
Standard CMOS passivation & end metal

Fully automated wafer level photonic and electrical probing

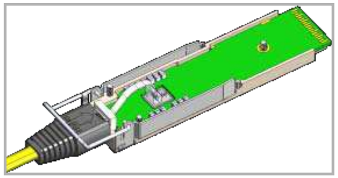
Die singulation



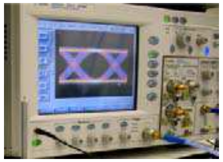
Automated laser attach



Packaging & automated fiber array attach



Automated test



PRODUCT

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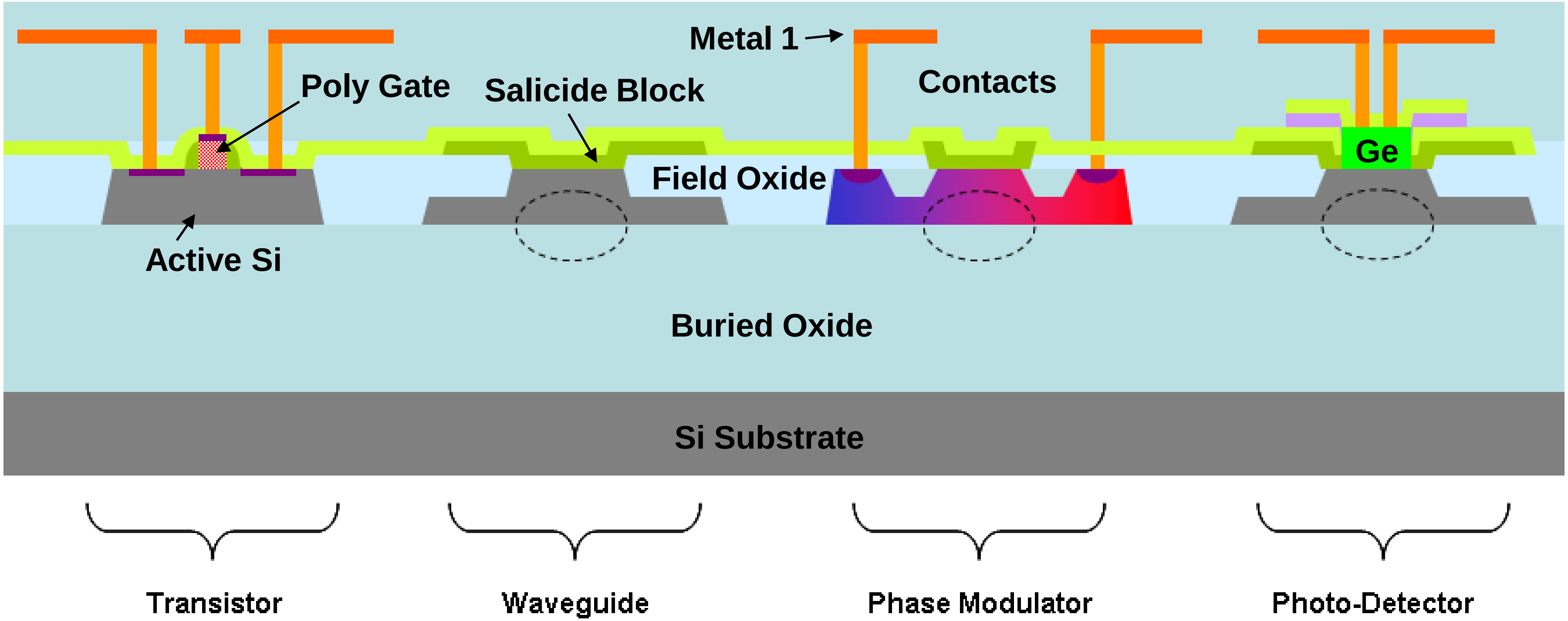
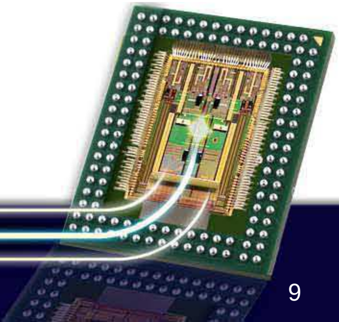
Photonics and Electronics on a Common Wafer

- Unprecedented level of optoelectronic integration in a low-cost commercial 0.13-µm SOI CMOS process using standard CMOS fabrication tool set

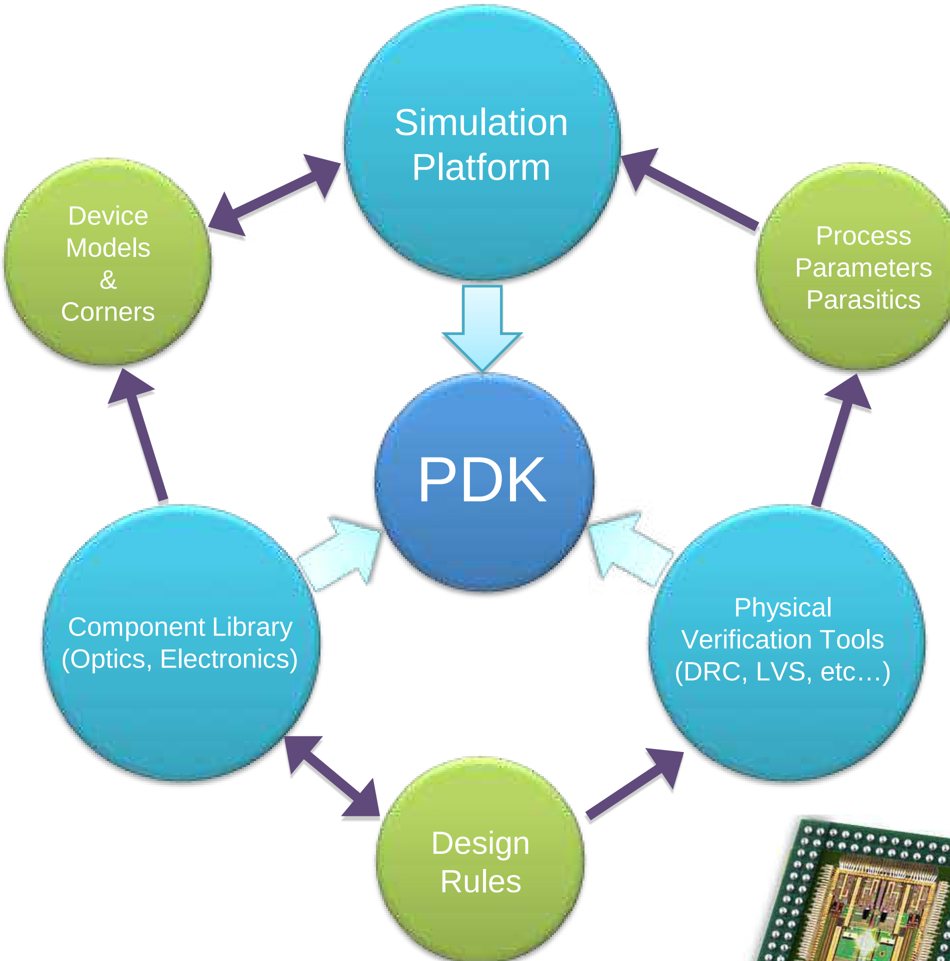


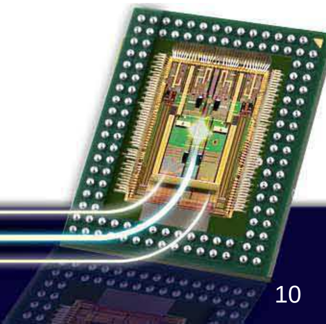


Design Tools

Standard industry CAD tools were enhanced to support photonics

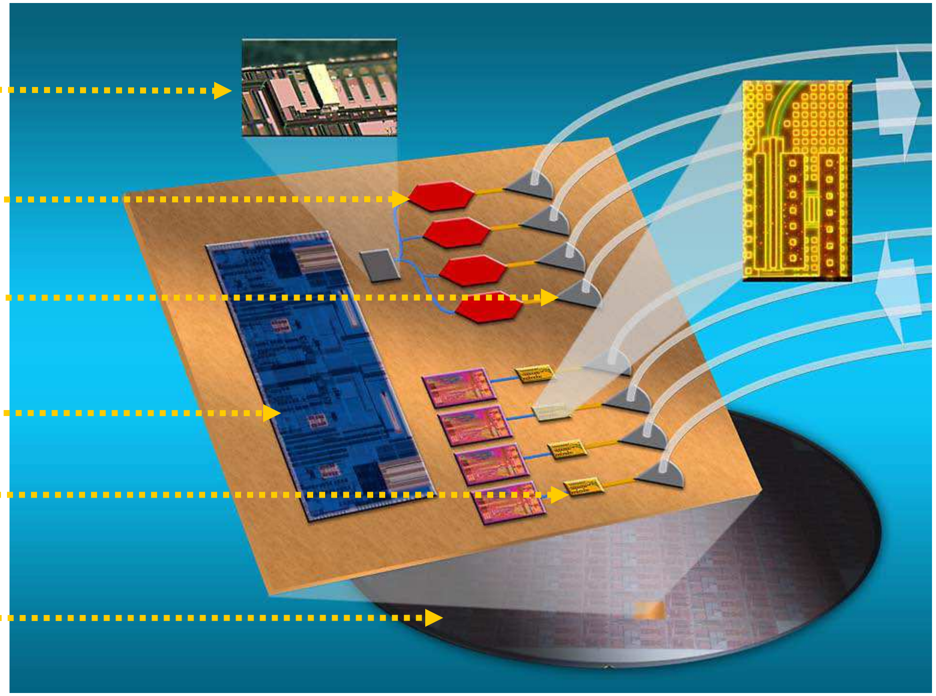
- DRC with optical process and device checks
- Optical LVS
- Simulation
  - OE simulation of complete systems
  - Combination of electrical and behavioral models used to represent optical and OE devices
  - Statistical models for accurate system performance prediction



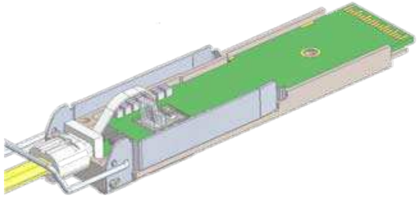


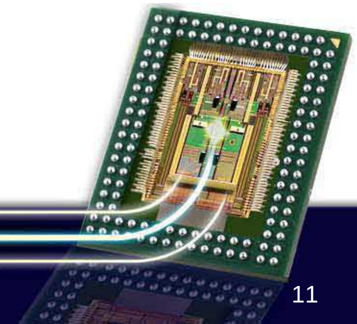
Integrated 40Gb/s Optical Transceiver in CMOS

- **Single Laser Powers 4 Lanes**
- **On-Die Modulators**
- **Fiber-to-the-Chip Coupling**
- **Integrated Electronics**
- **On-Chip Photo-Detectors**
- **Wafer Scale Testability**



Packaged in MSA Compatible Connectors





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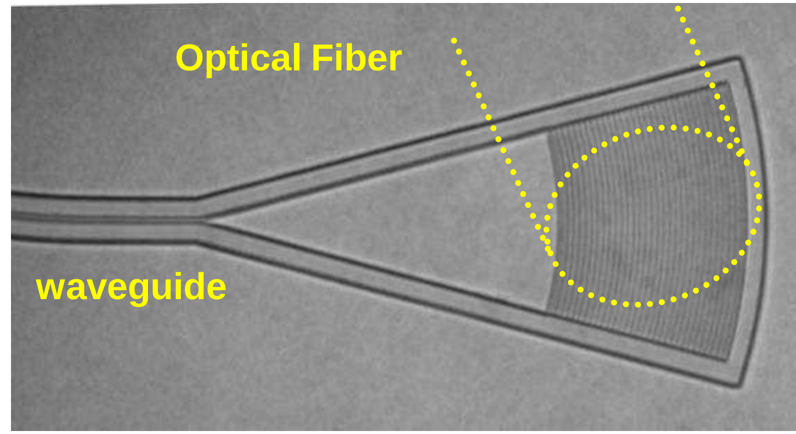
Light Coupling in and out of Silicon Die

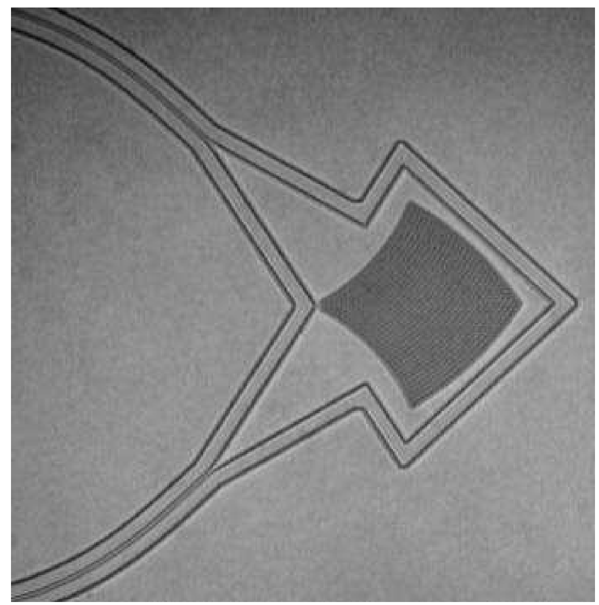
Single Polarization Holographic Lens

- **Function:**
  - Couple light out of die
  - Couple laser light in die
- **Design:**
  - 1-D Diffractive structure
  - Low loss by mode matching



Polarization Splitting Holographic Lens

- **Function:**
  - Couple light from standard single mode fiber into CMOS waveguides
  - Key for integrated optical receivers
- **Design:**
  - 2-D diffractive structure
  - Low loss by mode matching
  - Polarization diversity



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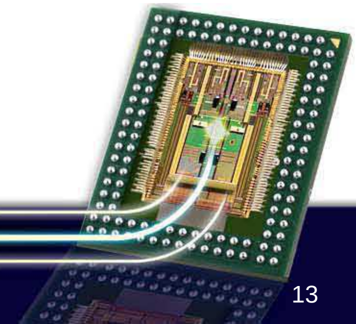
Power Reduction Strategy

- **Monolithic integration**
- **Understand your application**
  - Too much flexibility combined with feature creep can lead to inefficiency
- **Understand your technology**
  - Accurate process variation and statistical data avoids over-designing
- **Architectural innovation**
  - Reduced number of supply rails
  - Reduced optical loss translates to lower laser current
  - Low-current, reduced-range MZI phase calibration
- **Circuit-level innovation**
  - Reduce supply voltage
  - Receiver with process-based equalization
  - Transmitter with rail-to-rail output
  - Minimize overhead power (analog, bias, etc.)



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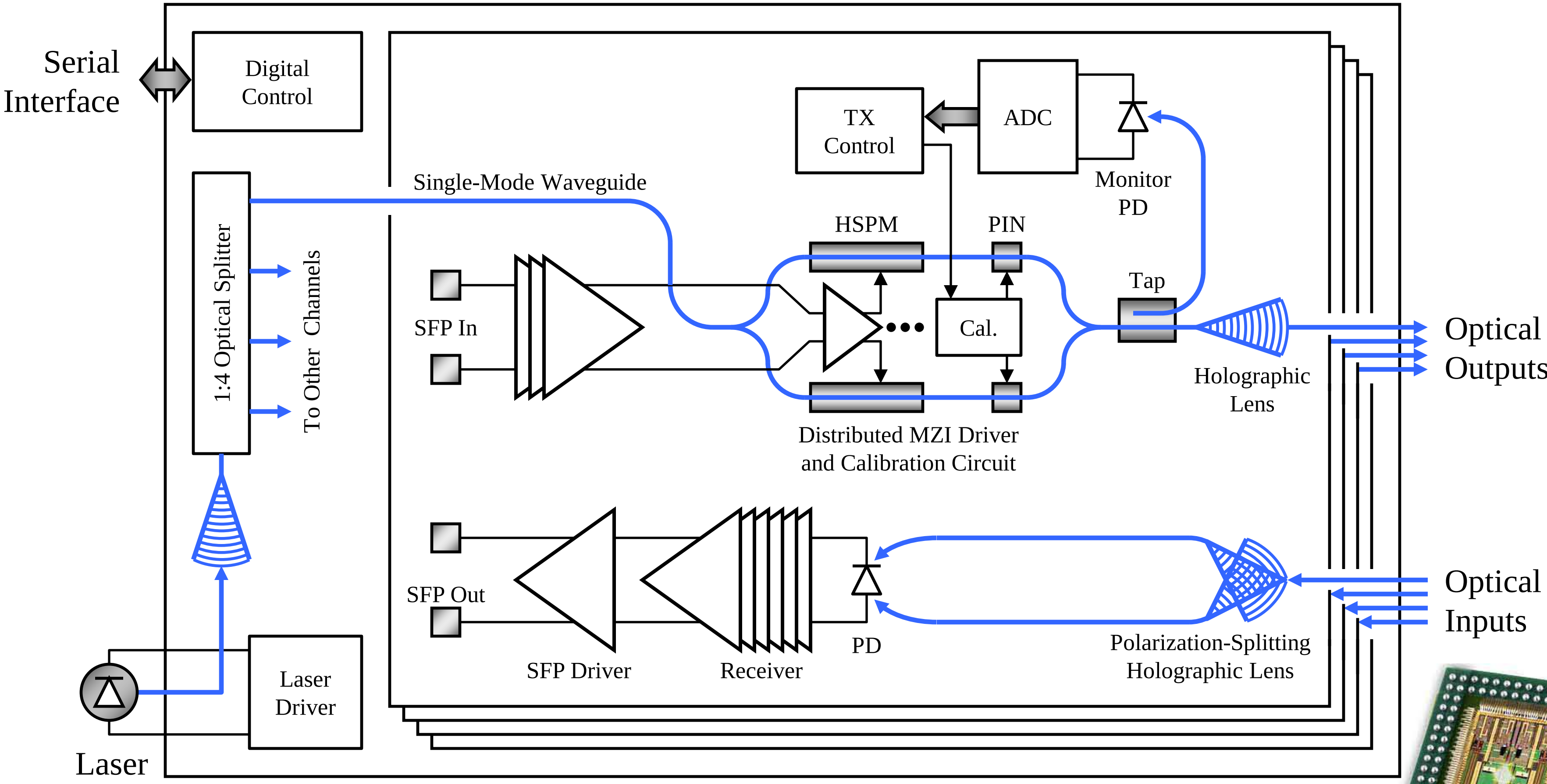
4-Channel Transceiver Diagram

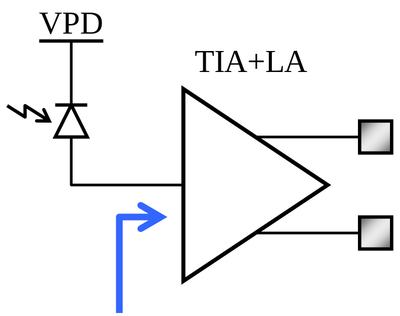
- **Single light source:** a continuous-wave 1490-nm III-V DFB laser mounted in a miniature, hermetically-sealed package with micro-optical components designed to couple light into the CMOS transceiver die



Integrated Photodetector

- Germanium waveguide photodetector has intrinsic parasitic capacitance approximately 100 times lower than its III-V counterpart
- Much lower interface parasitics as well due to proximity to the amplifier
- Automatic 3dB sensitivity advantage from differential coupling

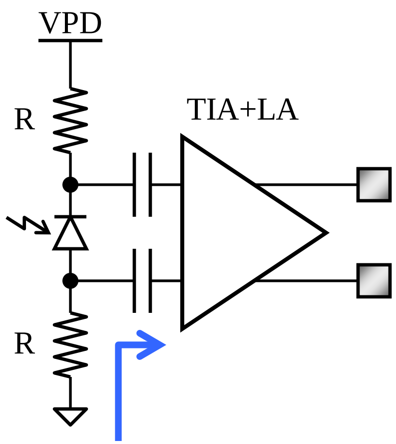
Traditional PD Coupling



Low input impedance (R_{in})

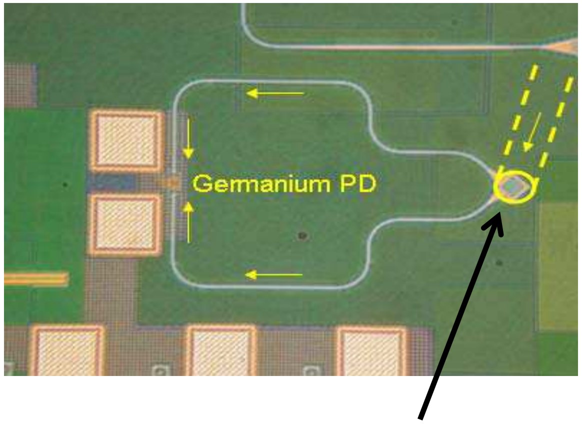
$$BW_{-3dB} \approx \frac{1}{2\pi \cdot R_{in} C_{PD}}$$

Differential PD Coupling

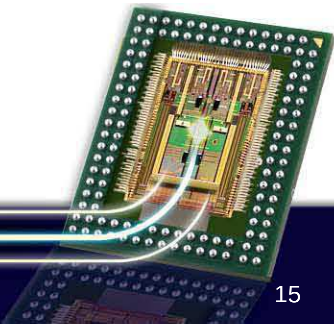


High input impedance

$$BW_{-3dB} \approx \frac{1}{2\pi \cdot 2RC_{PD}}$$



Polarization-Splitting Holographic Lens



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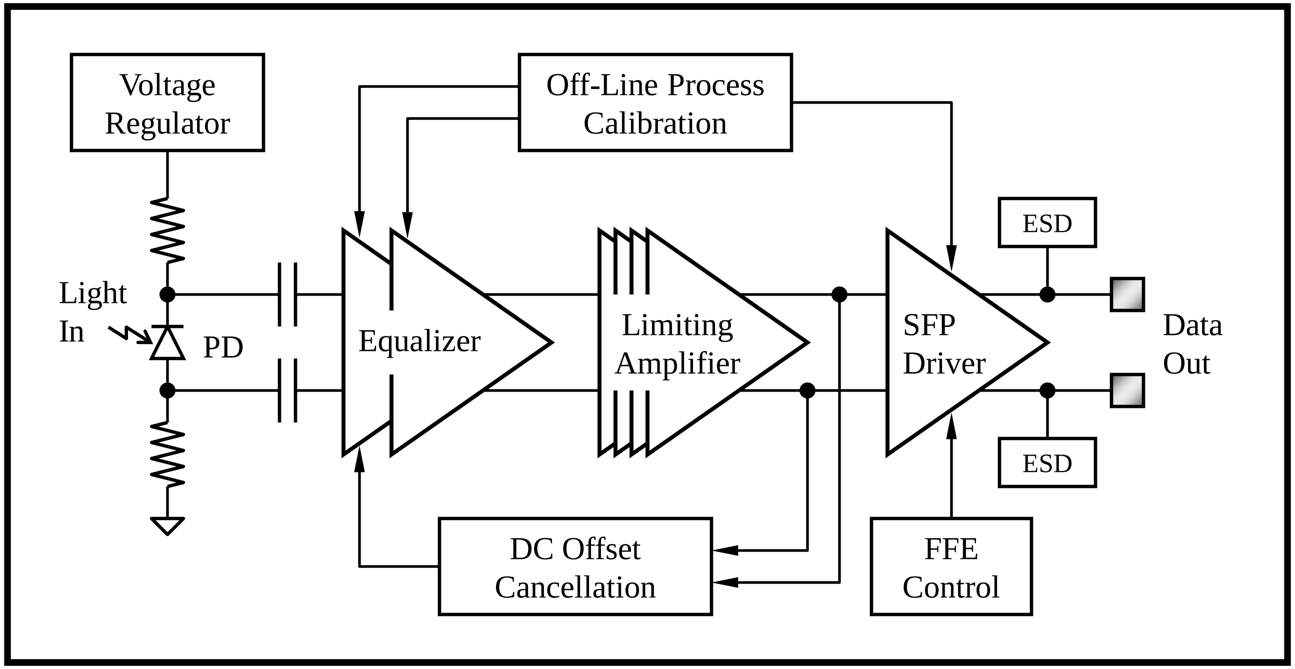
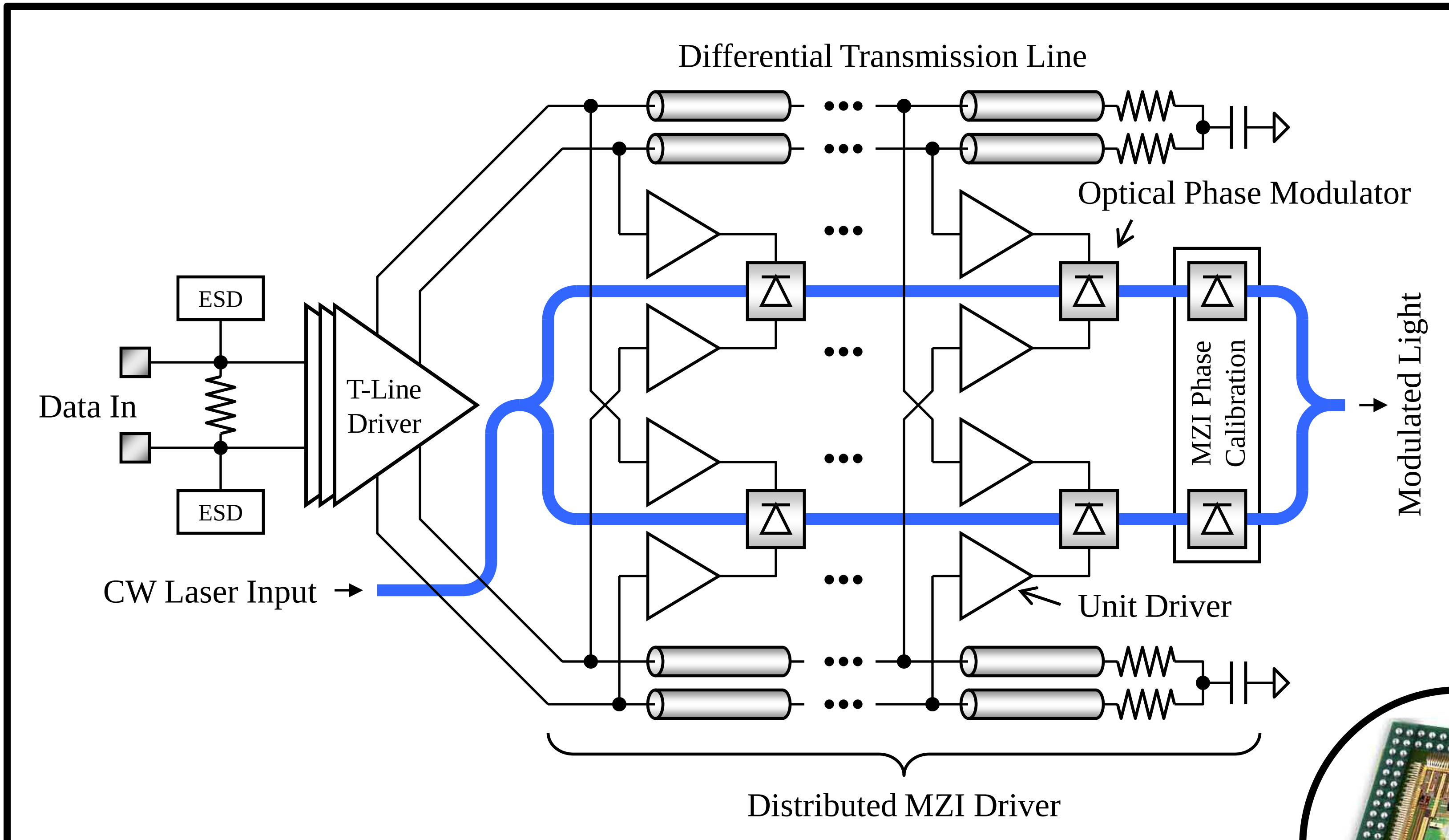
Integrated Receiver Diagram

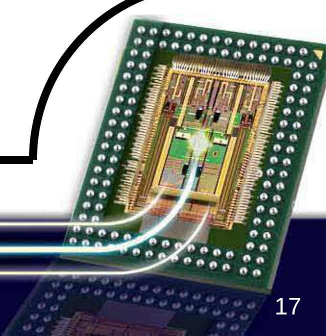
- Completely monolithic (integrated photodetector, regulator, amplifiers, and control/calibration functions)
- Optimized for low power
  - Low voltage circuit topologies
  - Off-line process calibration allows aggressive bandwidth enhancement with low DJ
  - Excess gain is avoided using accurate link budget and process corner models



Distributed Transmitter Diagram

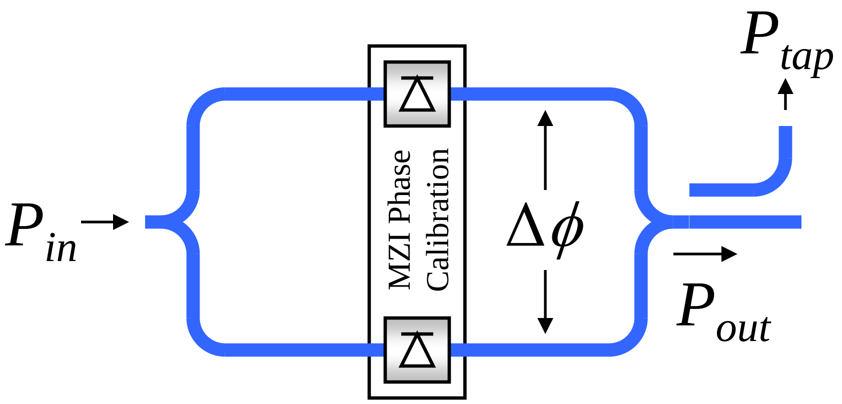
- Provides rail-to-rail voltage swing across optical phase modulators

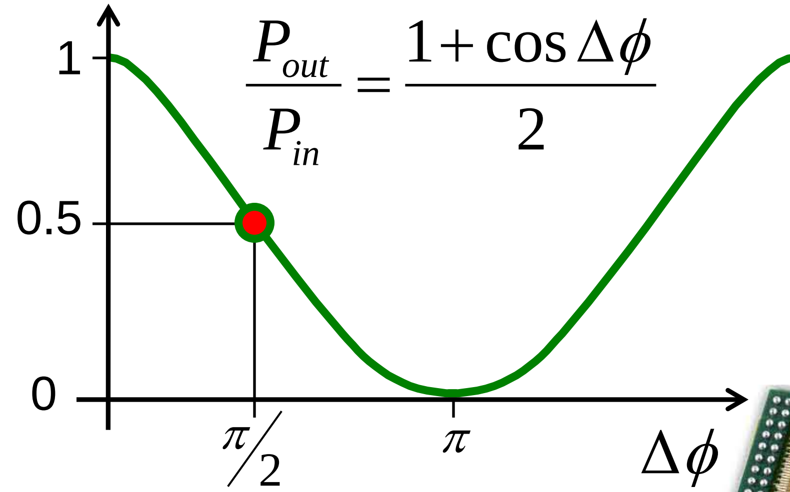




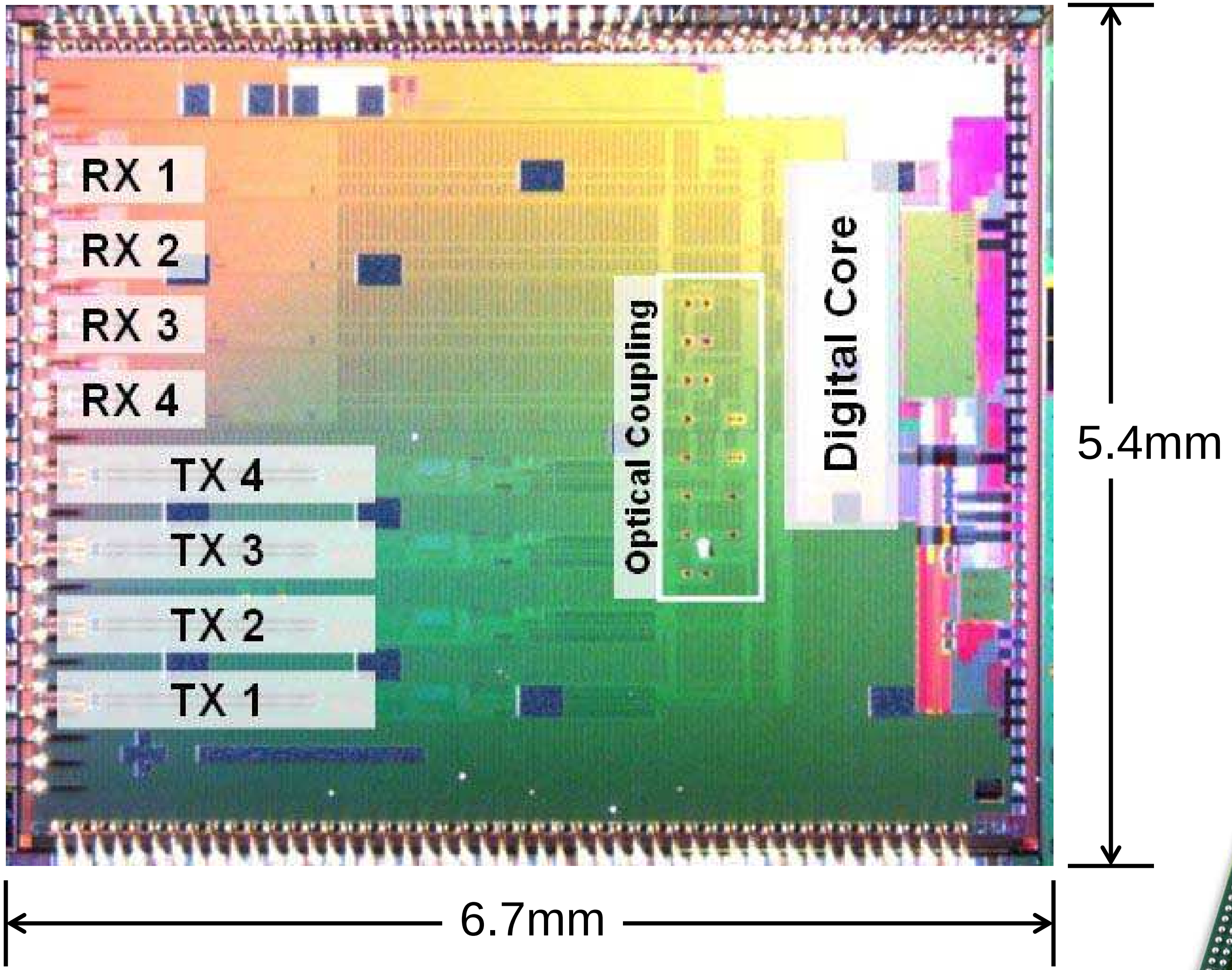
Mach-Zehnder Interferometer Control

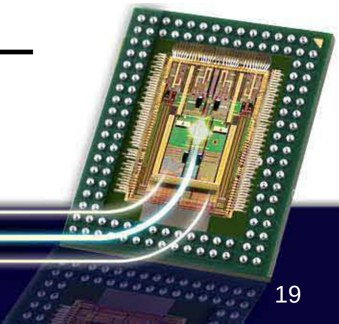
- Random process variations lead to phase mismatch between two symmetric interferometer arms
- Digital control algorithm sets a stable operating point for maximum extinction ratio and distortion-free eye
  - Optical tap and integrated Ge PD monitor MZI output
  - Low-current phase modulators compensate for mismatch





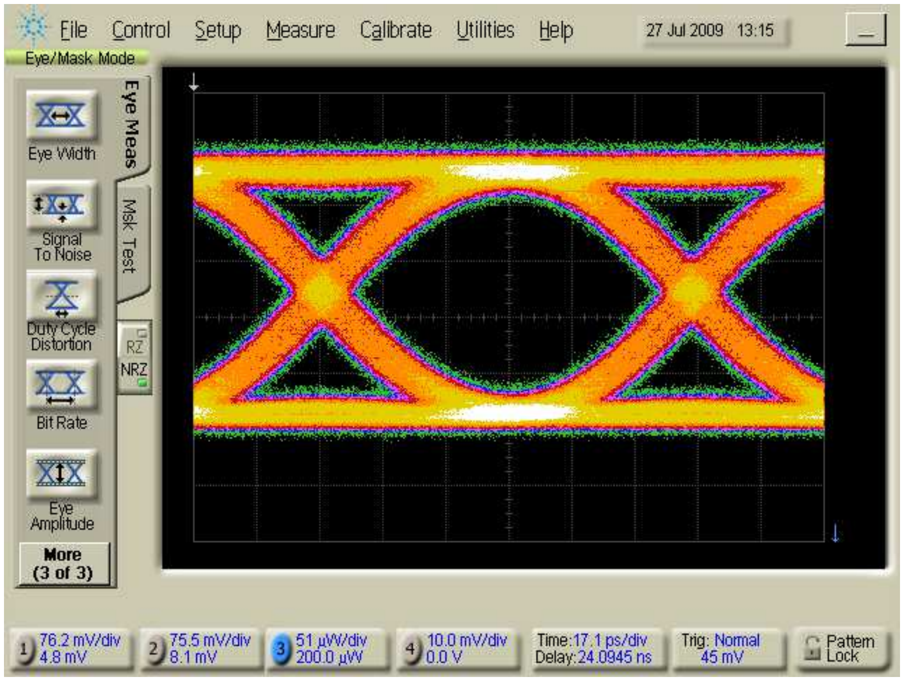
Transceiver Die Photograph



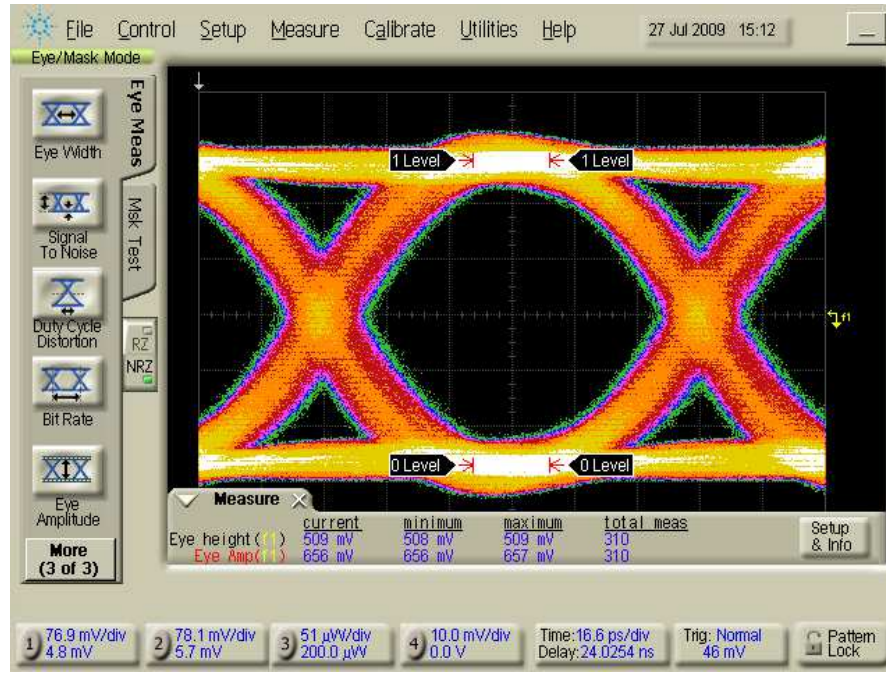


Measurement Results

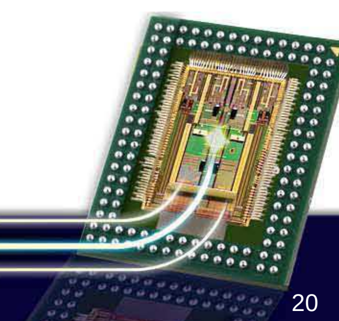
Optical Transmitter Eye 10Gb/s PRBS31 Pattern



Electrical Receiver Eye 10Gb/s PRBS31 Pattern



- Power significantly lower than 1W per end
- Complies with SFP+ and QSFP requirements



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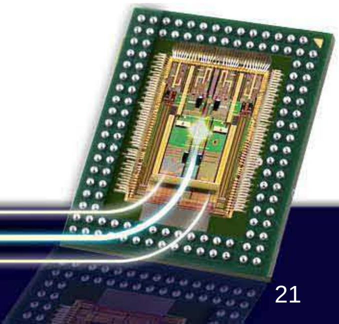
Si-Photonics vs VCSEL-Based Solutions

- **Lower Cost**
  - Integrated photodetectors
  - Single laser for multiple channels
  - Utilizes single-mode optical fiber cable → half the cost of multi-mode fiber
  - Monolithic versus hybrid receivers and transmitters → fewer components
  - Optical and electrical wafer-level testing → better module yield

- **Better Performance**
  - Scalable to 100Gb/s and beyond at 4km reach
  - Indirect modulation using MZI → laser parasitics do not matter
  - No modal dispersion → EDC not required

- **Better Reliability**
  - Fewer components
  - Utilizes continuous-wave DFB laser
  - Single laser for multiple channels
  - Laser is hermetically sealed
  - Lower laser current density



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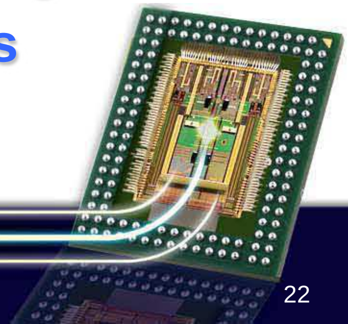
Conclusions

- As transistor scaling slows down, computing power can be increased through parallelism and system-level innovation
- That is where Silicon photonics comes in
  - Eliminates copper bottleneck
    - Rack-to-rack and board-to-board (currently)
    - Chip-to-chip and intra-chip (in the future)
  - Can be ported to advanced CMOS nodes and integrated with CPUs, memory, and other system elements
- **Silicon photonics is here!**
  - **Provides unprecedented level of optoelectronic integration**
  - **Enables low-cost, low-power connectivity solutions**



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Acknowledgements

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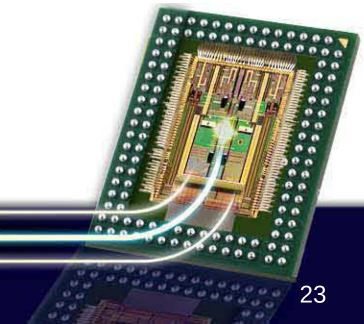

Thank You!