Ethernet Alliance
Technology Exploration Forum 2013
"The Future of Ethernet"

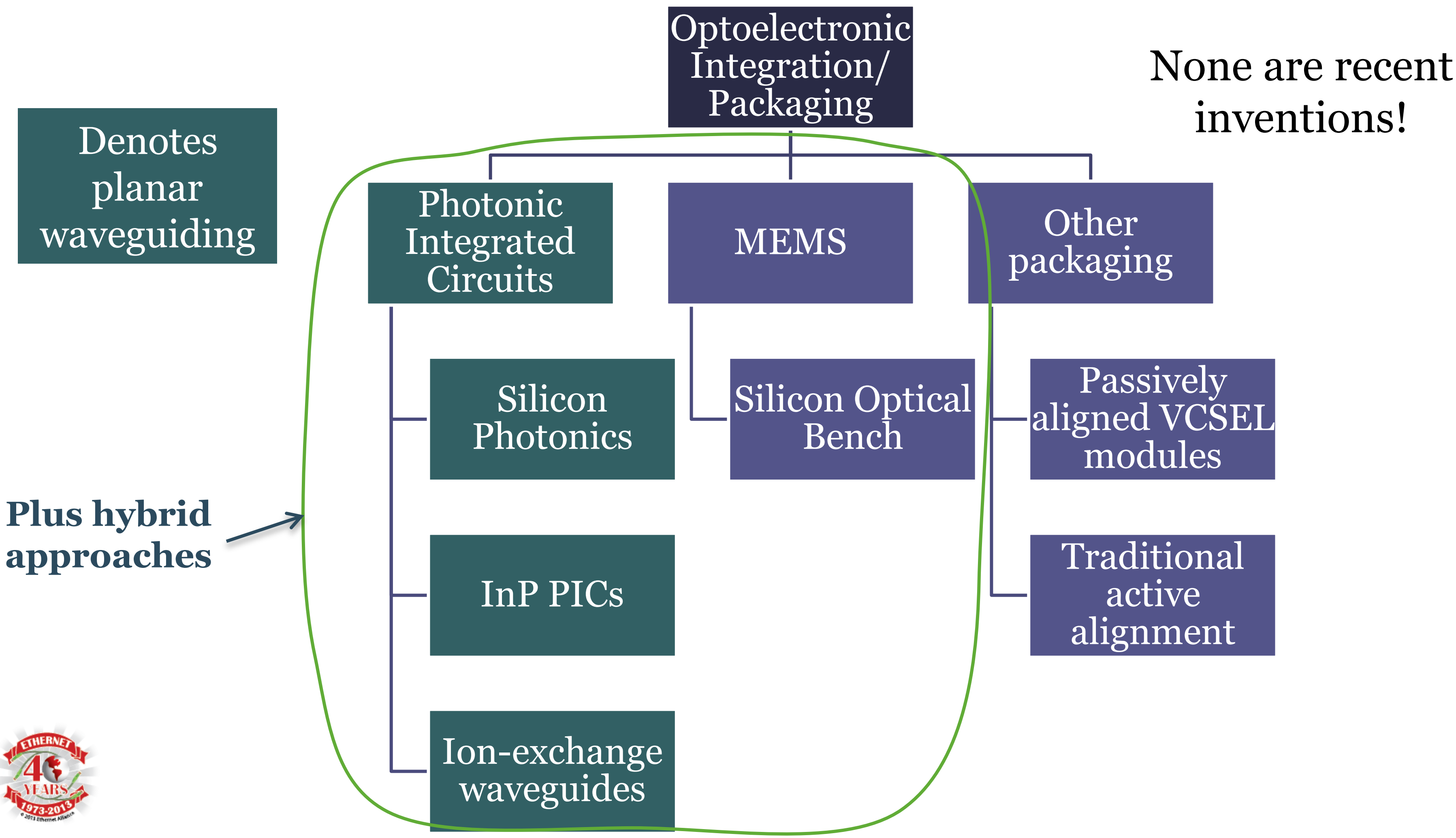
Technology Exploration Forum

The Promises of Photonic Integration

October 16, 2013

This presentation has been developed within the Ethernet Alliance, and is intended to educate and promote the exchange of information. Opinions expressed during this presentation are the views of the presenters, and should not be considered the views or positions of the Ethernet Alliance

A word about phraseology: Photonic Integration is broader than silicon photonics



Going Beyond the Hype

- Make transceivers using "standard CMOS processes" and they will be much cheaper.
- *"We expect a revolution in optics similar to the one the transistor brought to the world of electronics decades ago, beginning in late 2013."* equity analyst report
- A few years ago, Intel suggested its 'Light Peak' technology would bring high-speed optical links at consumer prices.

PANELISTS

- Chris Bergey: Luxtera
- Yigal Ezra: ColorChip
- Eric Hall: Aurrion
- Daniel Mahgerefteh: Finisar
- Valery Tolstikhin: Intengent

Moderator: Dale Murray: LightCounting

Key Questions for the Panel

- Has photonic integration really been tested by the market?
- Will photonic integration follow Moore's Law?
  - Unlike electronics, shrinking optical devices does not make them work better
- How will photonic integration underpin the advancement of Ethernet in data centers?
  - Will VCSEL products be displaced?
  - Will there be a dramatic shift to single mode?
    - Will the price premium for single mode be trimmed?
  - Or will there be a shift to 1300nm-optimized multimode fiber?
  - Is photonic integration the way to achieve high density with low power consumption? How?
  - Which approach to photonic integration will get us there at the lowest cost?

What Equipment Vendors Want

- **Lower power** and **lower cost per Gbps**
- Common solutions, but proprietary if lower cost
- Common form factor for all reaches.
  - Prefer to not go from CFP→CFP2→CFP4→QSFP
- Want 100G as it is lowest cost from a system perspective (not from a module perspective)

What Data Center Builders Want

- **Lower power** and **lower cost per Gbps**
- Low cost, high-volume 40G now
- Clear path to 100G without higher cost per Gbps
- Common solutions, but proprietary if lower cost
- Common form factor for all reaches.
  - Prefer to not go from CFP→CFP2→CFP4→QSFP
- Module reliability handled through fabric design, not raw hardware reliability
- Future proof infrastructures, though many are not ready to abandon multimode

Embedded Optical Modules vs. Pluggable Modules for Higher Density?

- Arista Networks offers a line card with twelve 100G-SR10 ports using embedded modules
- Microsoft wants this in single mode
- Will photonic integration bring competitive costs and longer reach to this new application?

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The Future of Ethernet

A Luxtera/Silicon Photonics Perspective

Chris Bergey
cbergey@luxtera.com

Trend 1: DISRUPTIVE ECONOMICS

Comparable to

Traditional Telecom/Enterprise Datacenters

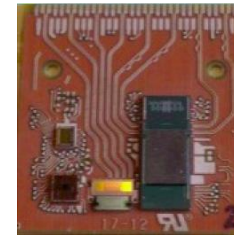
- Lots of legacy equipment/interfaces
- Purchase through traditional channels
- Equipment amortization over 5-10+ yrs

Web2.0 Datacenters

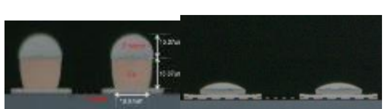
- Cost to deliver X petaflops/in Y volume paying Z in cooling
- Equipment is disposable/design a totally different datacenter for a new application
- Move quickly to disruptive HW

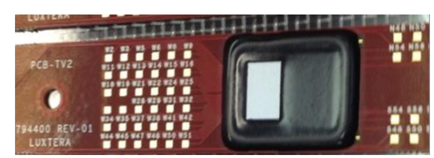
- Cloud = Bandwidth and aggregation of HW spend
  - Will lead innovation vs. traditional enterprise
  - Huge spend
  - Enterprise will adopt later and leverage due to drastic difference in cost and power/bit
- *Great opportunity for disruptive technologies*

Trend 2: THE PACKAGE/SI PROBLEM



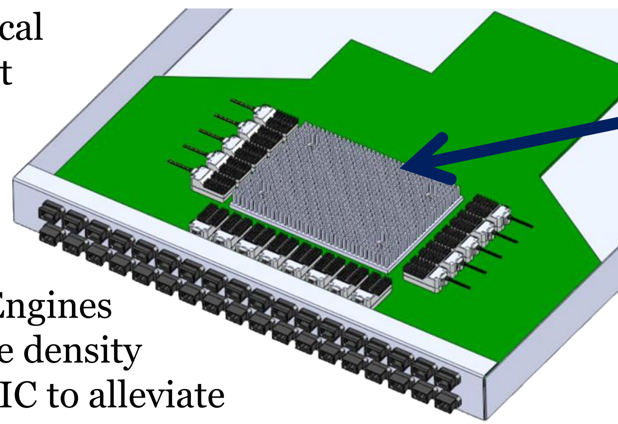
- It doesn’t matter how good your material system is at a function, system cost and performance are often determined by the packaging and assembly
  - Lots of new Silicon Photonics/Silicon Bench companies:
    - Why use silicon? Leverage manufacturing infrastructure (CMOS, MEMS industry)
- Proximity between electronics and optics becomes a strong requirement at high data rates
  - Signal conditioning and retiming is very power hungry even in the latest technology nodes and it is also expensive
  - Each interface in the electrical single path is a source of loss and noise and cost, traditional approaches like wire bonds can only be used in limited cases.
- *Silicon Photonics allows:*
  - *Higher levels of integration*
  - *Tight coupling of electronics with photonics by monolithic integration or 2.5D packaging*



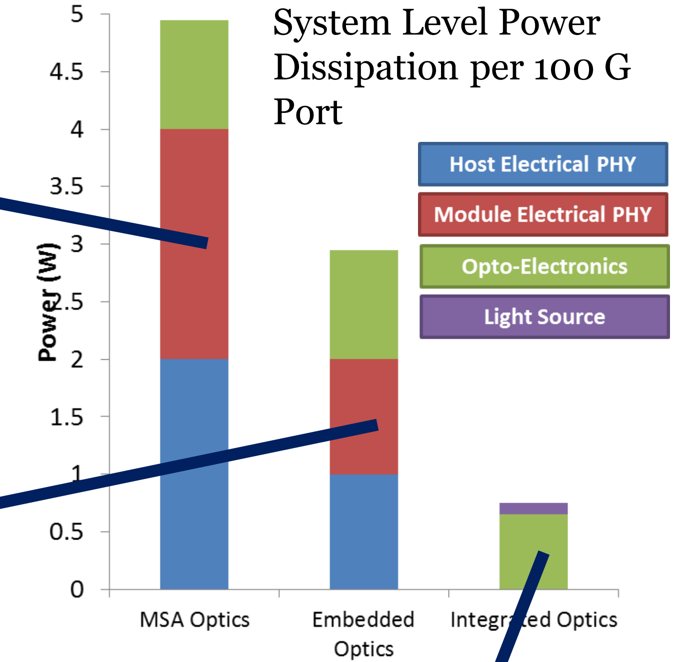


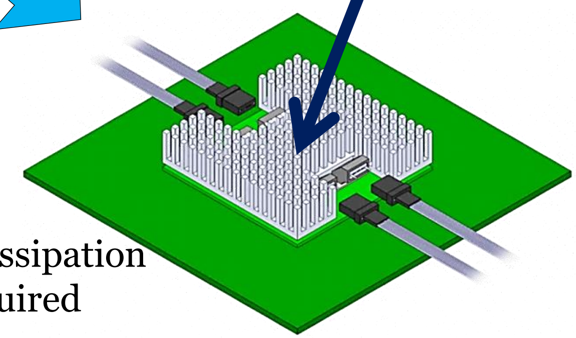
Technology Evolution

CONTEMPORARY:
- MSA compliant Pluggable modules and AOCs: QSFP, CXP,…
- Considerable SI issues (electrical connectors, long traces on host PCBA)
- ~15-20dB channel



EMERGING:
- Embedded Optical Engines
- Addresses front plate density
- Located closer to ASIC to alleviate SI issues (shorter traces)
- Very high reliability required
- ~5-15dB channel





FUTURE DIRECTION:
- SoC Integration
- Smallest form factor
- Lowest system power dissipation
- Very high reliability required

Back to Trend 1: Follow the Silicon

- Front plate and silicon density

Arista 7050S-64: 48 x 1/10GbE SFP+ and 4 x 40GbE QSFP+ ports

Arista 7050Q-16: 16 x 40GbE QSFP+ and 8 x 10GbE SFP+ ports

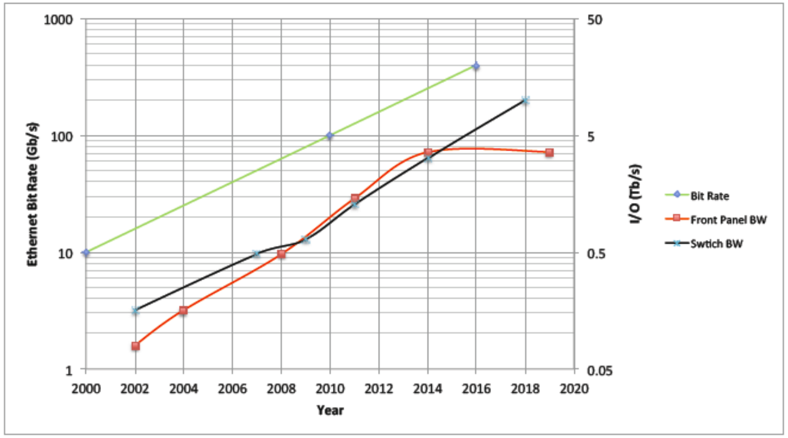


Figure 1. Ethernet bit rate in comparison to front panel BW and switch BW *

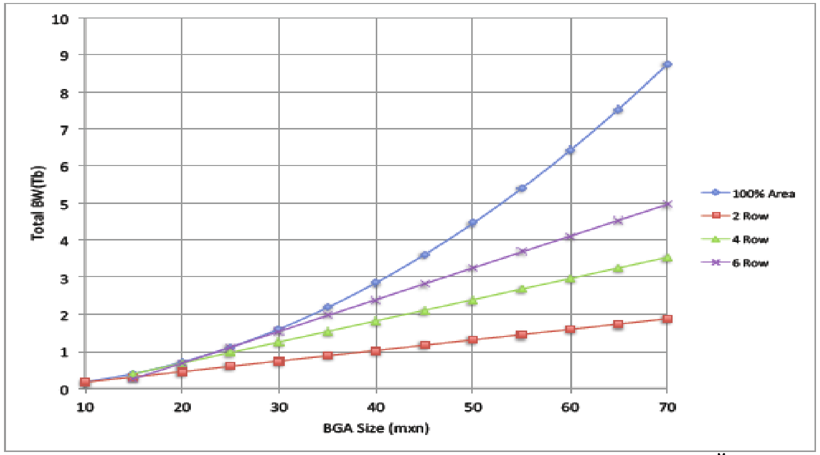


Figure 3. Total I/O BW for Given Package Size *

- Is the I/O even routable out of the package?
- Have to move to 25G I/O
- Will cause fast 100G adoption
  - 40G = 2x20G
  - 100G = 4x25G

*Source: Ali Ghassi, Broadcom, IEEE GFP paper: "Is There a Need for on-Chip Photonic Integration for Large Data Warehouse Switches"

Trend 3: SMF- What cost premium?

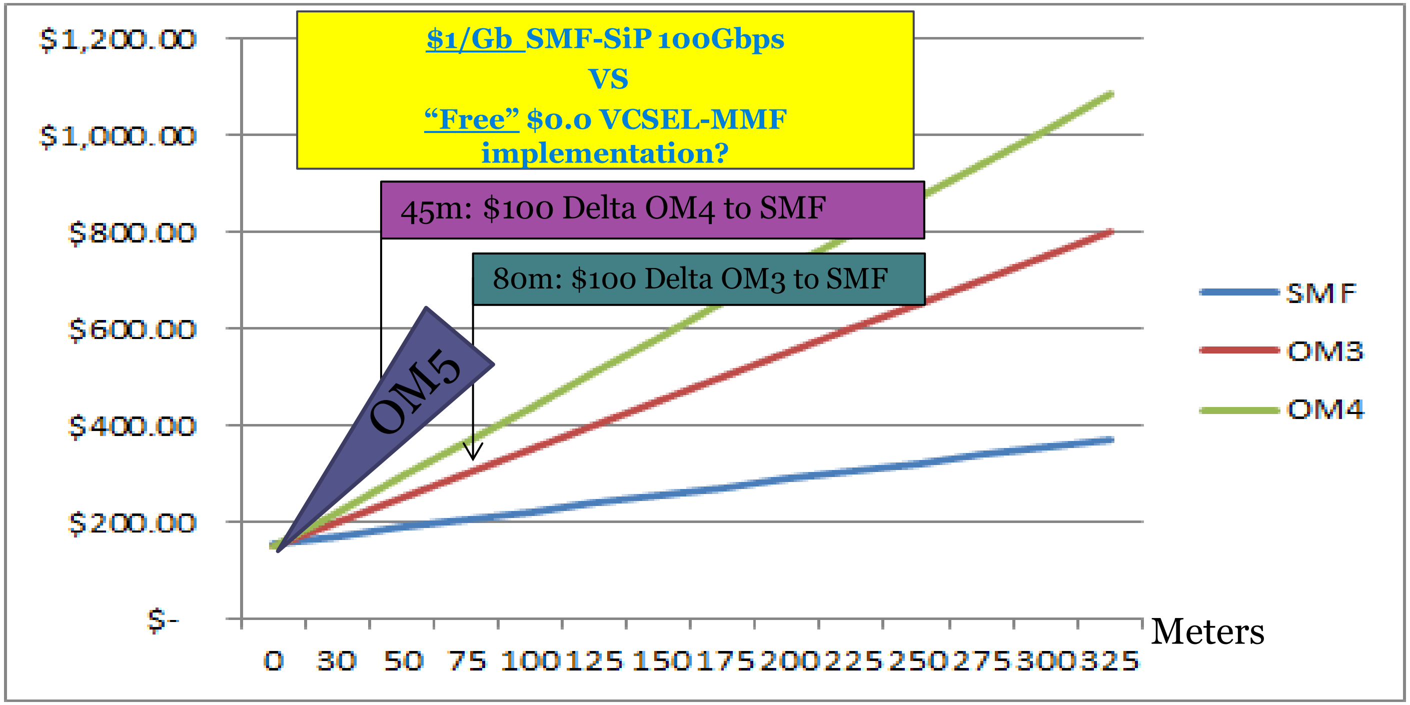
Fiber + Connectors

Inputs:

- Fiber: 12f (SMF: $0.67/m; OM3: $2.00/m; OM4: $2.88/m)
- Connectors: 4 pairs for structured wiring (8 half connectors)
  + 2 half connectors at module boundary

Only considers initial installation, now DC are looking at 10-20 yrs for fiber vs. 3-5 yrs for transceiver
Only Parallel SMF has scalability roadmap at reach requirements

Fiber/Connectors



With $1/Gb 100G for Both SiP/SMF & VCSEL/MMF Transceiver implementations

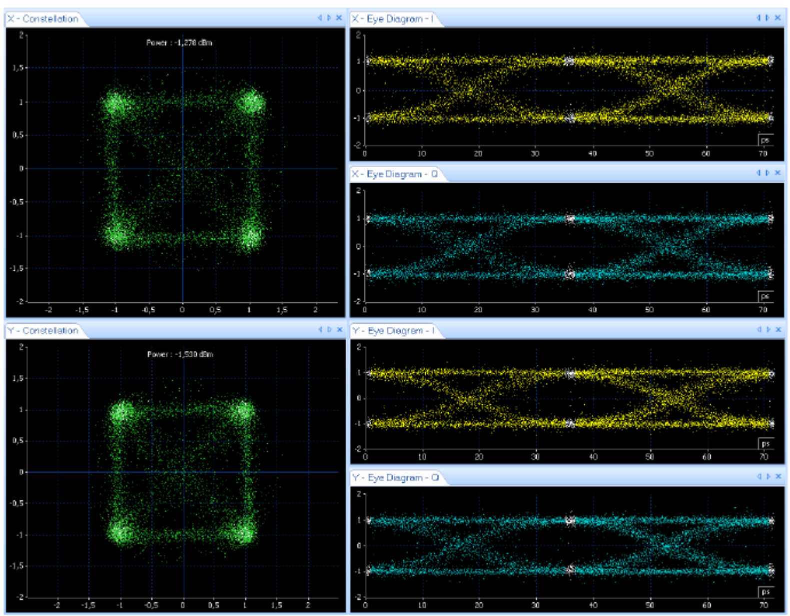
	30m
SMF	$ 175.73
OM3	$ 210.20
OM4	$ 236.48

	100m
SMF	$ 222.51
OM3	$ 350.30
OM4	$ 437.88

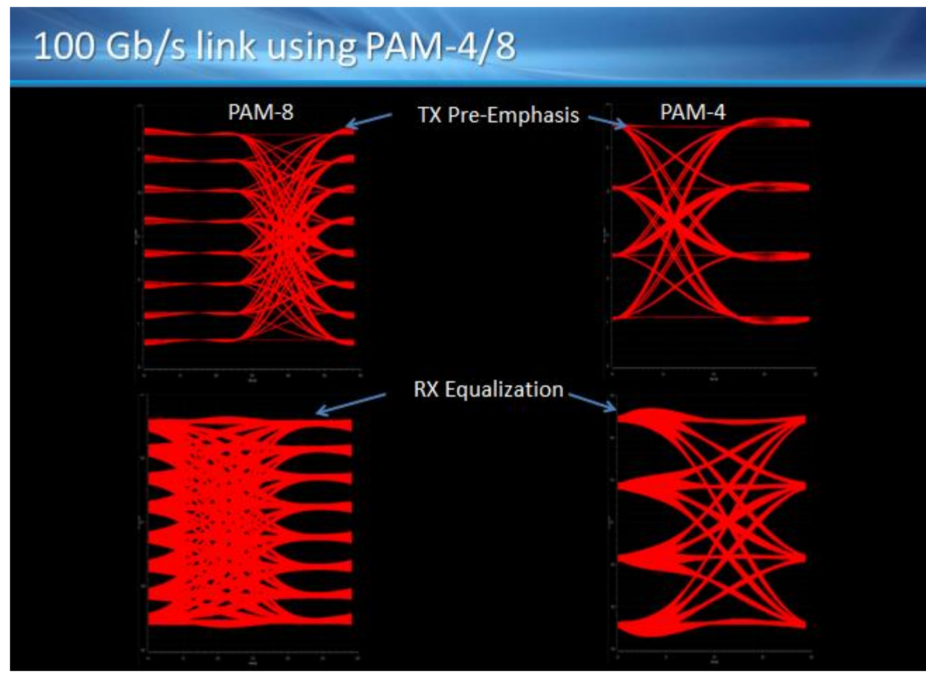
	300m
SMF	$ 356.16
OM3	$ 750.57
OM4	$ 1,013.32

Trend 4: EMBRACE THE TRANSISTOR

- Tremendous success with advanced modulation
  - Photons are EXPENSIVE compared to transistors and don't scale with Moore's law
    - Answer: Apply electronics to help with joules per bit
  - Coherent transceivers 40G/100G/200G and beyond
  - Optical PAM example



Constellation diagram directly after transceiver 100G DP-QPSK



Trend 5: WE NEED TO LISTEN TOO

- The receiver is as important as the transmitter
  - Silicon Photonics transmitters should only be half of the solution
  - Tough to differentiate vs. directly modulated solutions if traditional receivers are required
    - 1 receiver vs. 100 receivers equals same processing steps
  - Receivers are difficult but possible
    - Also allows for a better transmitter design through the use of feedback loops, calibration, etc.
  - Receivers can have excellent performance at minimal cost
    - APD receivers in Silicon are less attractive due to voltage requirements and stability issues

Who is Luxtera?

Founded in 2001, Luxtera is widely recognized as the industry leader in Silicon Photonics

- World's only complete Si Photonics technology platform
- Extensive IP portfolio
- Enables single-chip multiple channel optical transceivers & full SoC integration
- Proven in Volume Production with over 2Mu 10Gb+ channels shipped
- Sustainable advantages on scalability, density, power, reach, reliability and product cost

Achievements: first to commercially deploy silicon photonics in volume products

- First commercial application: 4x10 Gbps AOC (since 2009)
- Over 1.48 Billion failure free operating hours of Silicon Photonics transceivers
- Complete product offering for 40GbE and 100GbE

Conclusion

- There are exciting opportunities occurring in telecom and datacom for optics to be disruptive
  - Web2.0 build out represents a more rational market than traditional communications infrastructure with enough dollars to make it worth chasing
- Electrical/copper power consumption and reach/cost of materials are providing an opportunity for more wider use of optics
- Smarter photonics with tight coupling of electronics in both NRZ and modulation methods will be successful to best utilize the Gb/photon.

ColorChip SystemOnGlass™

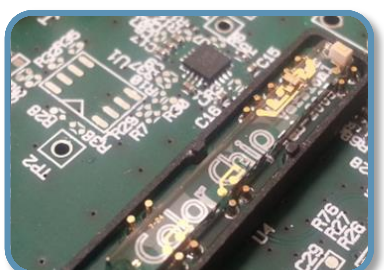
Revolution in Photonic Integration

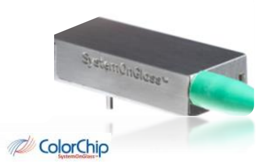
Advanced Optical Communication Solutions

Speaker: Yigal Ezra
VP Business Development

Ethernet Communications – Cable Transition to Fiber

Vs.





Cable Limitation

Cable (Copper, AOC) faces practical limits over 10G due to power, density, weight, distance, EMI requirements

Industry standard Single Mode Fiber (SMF)

Displacing Copper/AOC cabling for many rack-to-rack interconnects and is poised for board-to-board

Proprietary EOMs

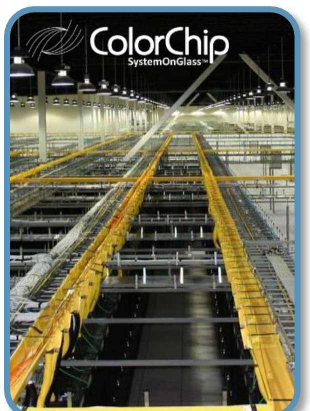
Proprietary solutions such as ColorChip WDM NXN WDM engine can deliver 10X over a standard fiber

Transition to all fiber solutions – Rack/Rack-to-Rack Distinction

North-South

At 10G cables are still dominant
25G and beyond – will transition to optics

Key Tradeoffs: **Price/Speed/Space/Power**



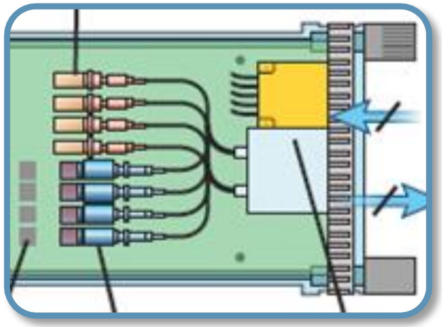
East-West Interconnect

Single Mode Fiber becomes more commonly used
500M and less dominance of AOCs (require redundancies) and PSM (with the challenging MPO connector)
Beyond **500M** SMF+LC is preferred

Key Tradeoffs: **Price/Distance/Simplicity/Reliability**

Photonic Integration - What it enabled us to achieve so far?

High Density / Low Power Pluggable Transceivers



40GBASE LR4 CFP

CFP / Bulk Optics

Limited serial active components and the free-space-optics approach drove cumbersome, large solutions and high power dissipation

Vs.

40GBASE LR4 QSFP+

QSFP+ LR4 / Photonic Integrated Circuit

ColorChip's Transceiver consists with a nested 4XNλ Mux/Demux, WDM based TOSA/ROSA integrating active components and obtaining low power QSFP+

Photonic Integration - What it enabled us to achieve so far?
Manufacturability / Low Cost

Wafer Scale Platform

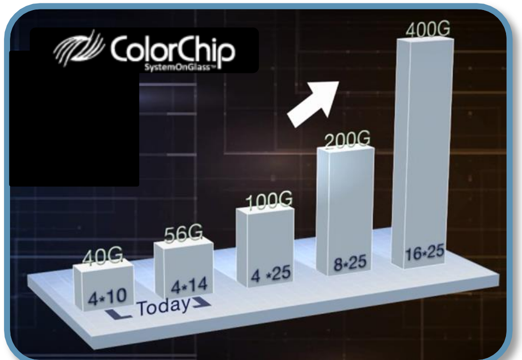
Fully automated production of Planar Lightwave Circuits (PLC) on a wafer scale allows mass production platform

Automated Photonic Integration

Photonic integration done by proprietary pick-and-place automated machines allowing scalability and repeatability of production

Manufacturability & Repeatability ***ensures***
Mass Production, High Yield, Reliable Solution

Photonic Integration – Future outlook
Higher Rate Compact Pluggable and Embedded Modules

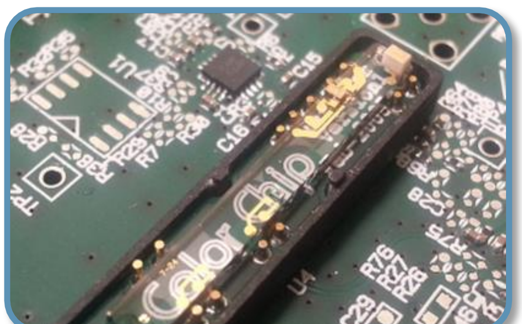


Higher Rate/Lower Power Pluggable Transceivers

- Today: 40GBASE & 56G IB LR4
- 2 years: 100GBASE LR4
- Beyond: 200GE, 400GE

(Today and 2 years: QSFP+/28)

DML | VCSEL/DFB | Modulators



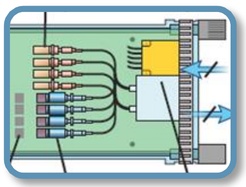
EOM- Embedded Optical Modules

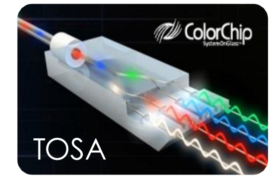
- Today: 100GE MM SR (10x12)
- 1 year: 100GE SMF LR (4X25)

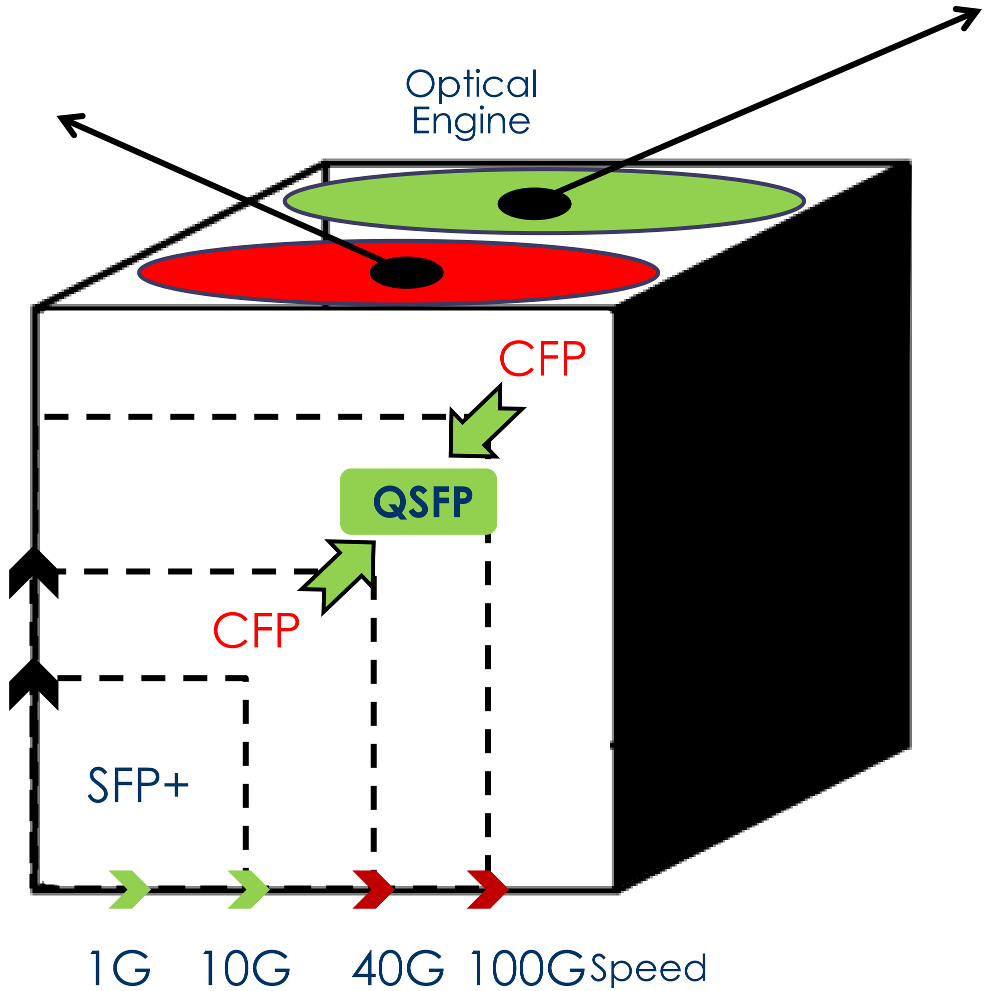
We will achieve higher rate, compact, lower power and cost effective solutions by implementing the principles ColorChip laid out with our photonic integration – SystemOnGlass™ approach

Breaking through industry linearity

Speed: determined by active optical components

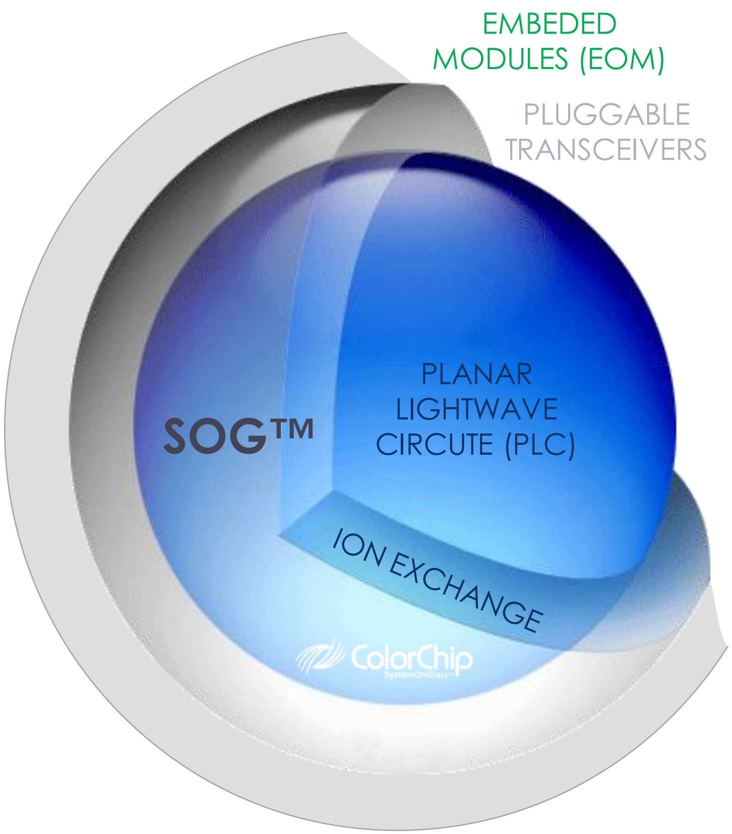


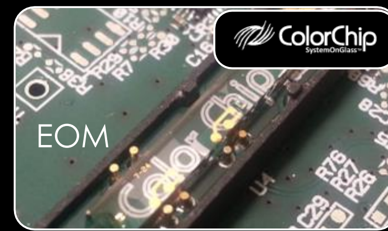




Form Factor/ Density

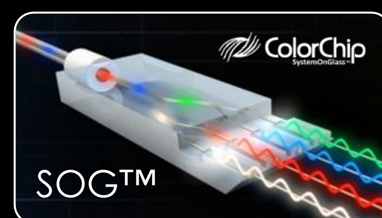
Photonic Integration



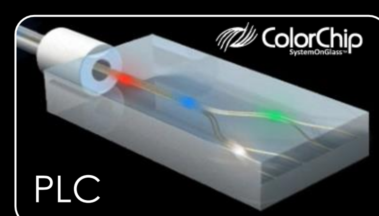


- Embedded Optical Module
- 100G and Beyond
- Easy integration to PCB
- Optically integrated to front panel (Eliminating Copper Traces)
- Fiber to Fiber Connectivity

- Pluggable TRX – **QSFP**
- **40G, 56G, 100G and Beyond**
- Duplex SMF
- Long Reach
- Low Power : Class 1-4



- SystmemOnGlass – Hybrid Photonic Integrated Circuit (PIC)
- Active optical components: VCSEL, DFB, modulators, PD, etc.
- Compact optical head (TOSA/ROSA)



- Wafer Scale PLC
- Nested Mux/DeMux
- Optimized Fiber Coupling

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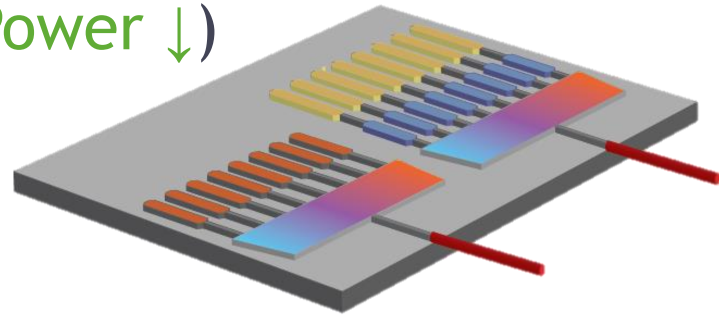
Complete silicon photonics integration platform

Eric Hall
Aurrion

Photonic Integration Philosophy

- Silicon integration platform…
  - Enables compatibility with silicon fabrication and packaging infrastructure (Cost ↓)
  - Yields high complexity photonic circuits (Density ↑)
  - Shortens electronic-photonic interconnect (Power ↓)
- Integrating the lasers…
  - Simplifies packaging (Cost ↓)
  - Enables WDM (Density ↑)
  - Reduces power consumption (Power ↓)



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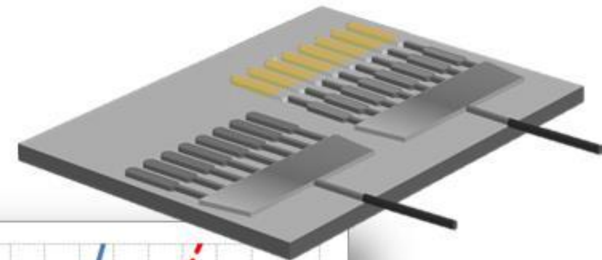
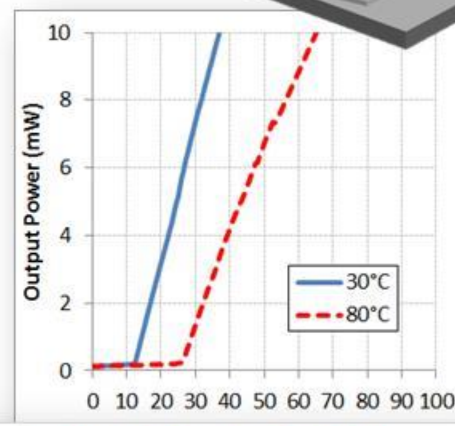
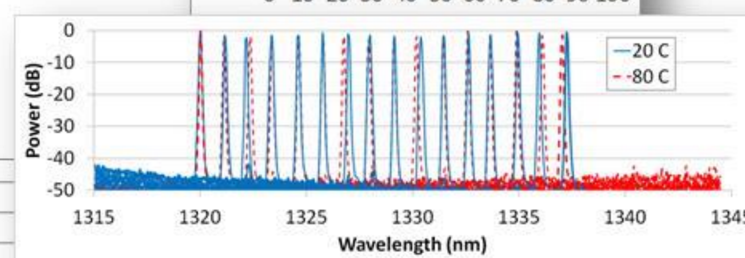
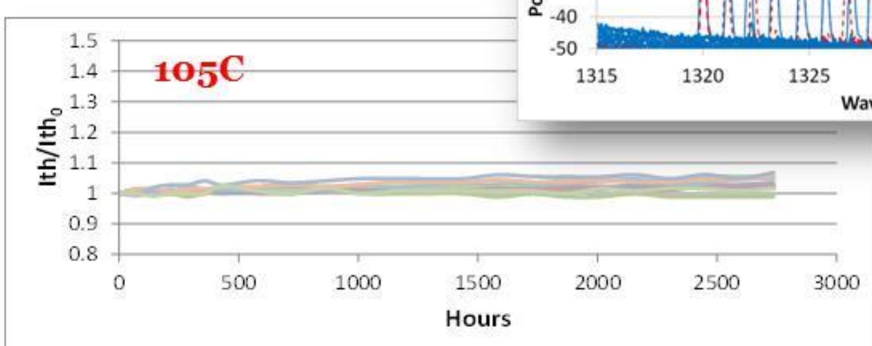
Integrated WDM Lasers

- Lasers on silicon with high efficiency (15%) at 80C
- Locking to WDM grid (200GHz-800GHz) across temperature









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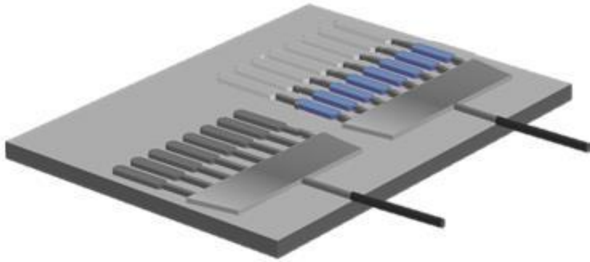
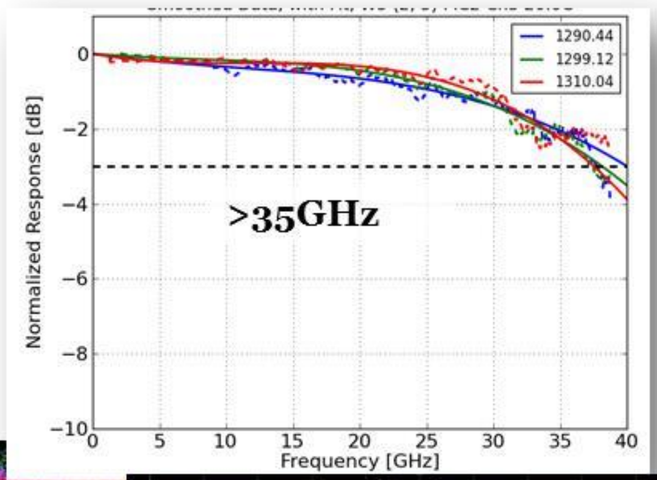
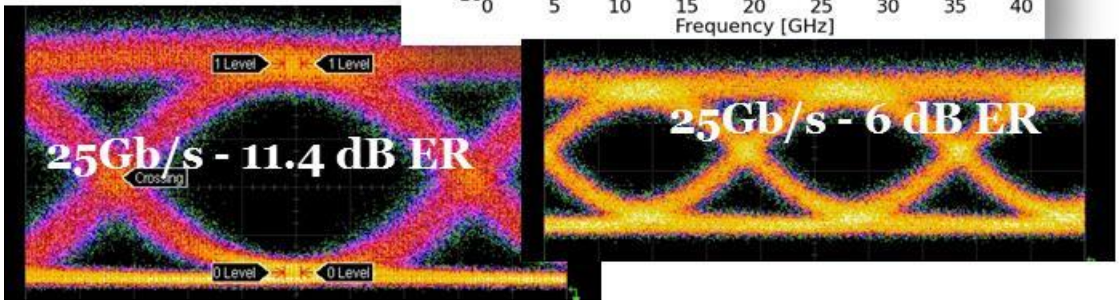
High Speed Modulators



- III-V/Si electroabsorption modulators (EAMs)
  - Compact (<200um)
- High performance
  - 3dB BW > 35GHz
  - IL < 3dB
  - 11dB ER @ 3V
  - 6dB ER @ 1.5V





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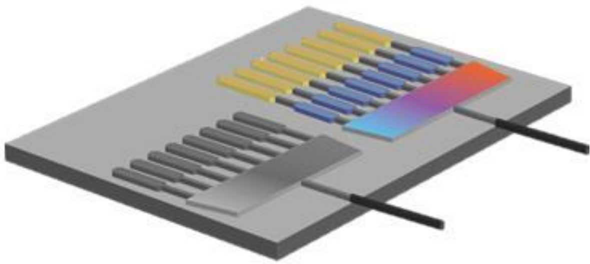
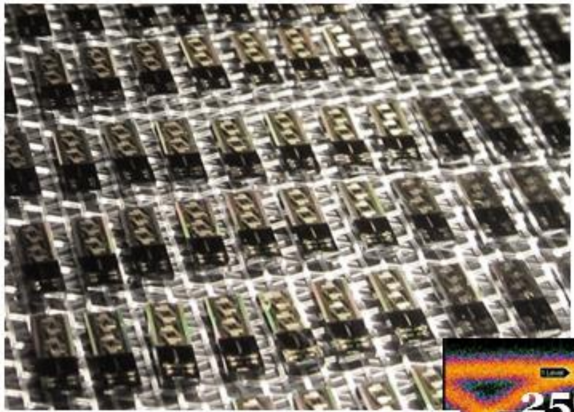
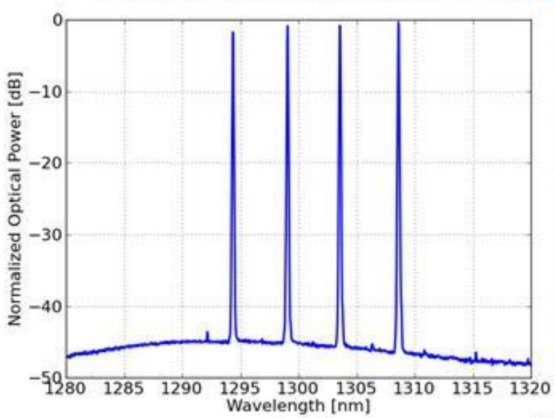
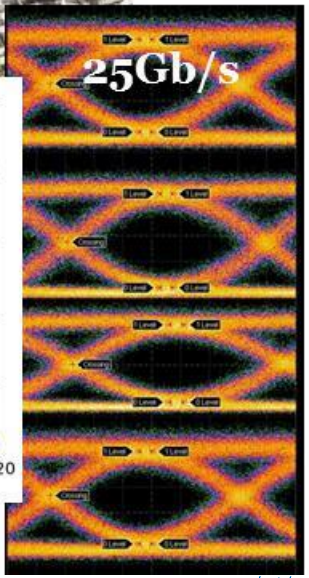
Transmitter PICs

- Single chip silicon photonics WDM transmitter
  - 4x WDM lasers
  - 4x 25Gb/s modulators
  - Multiplexed to SMF









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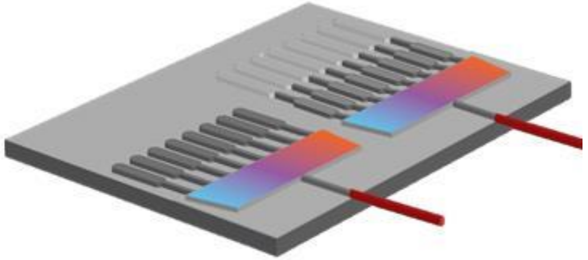
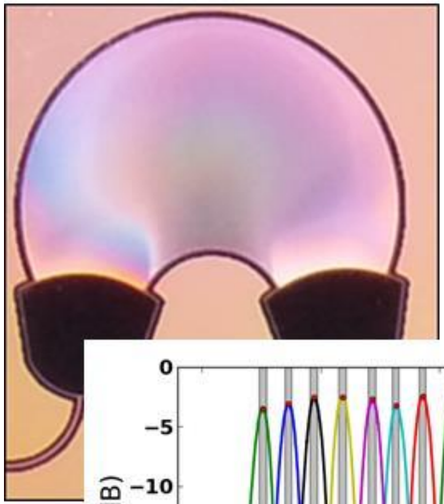
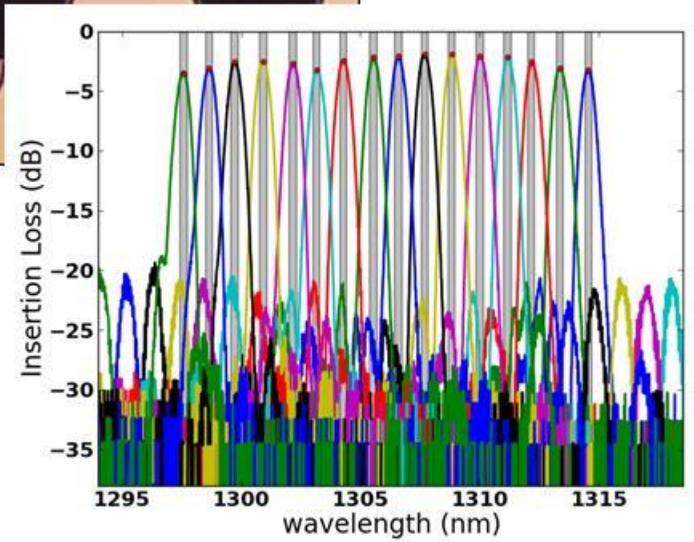
Low Loss Passives



- Low-loss (<1dB/cm) silicon waveguides and low-loss crossings
- High yield complex structures with 8” fabrication tooling





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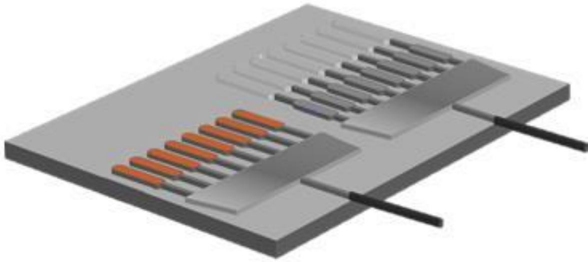
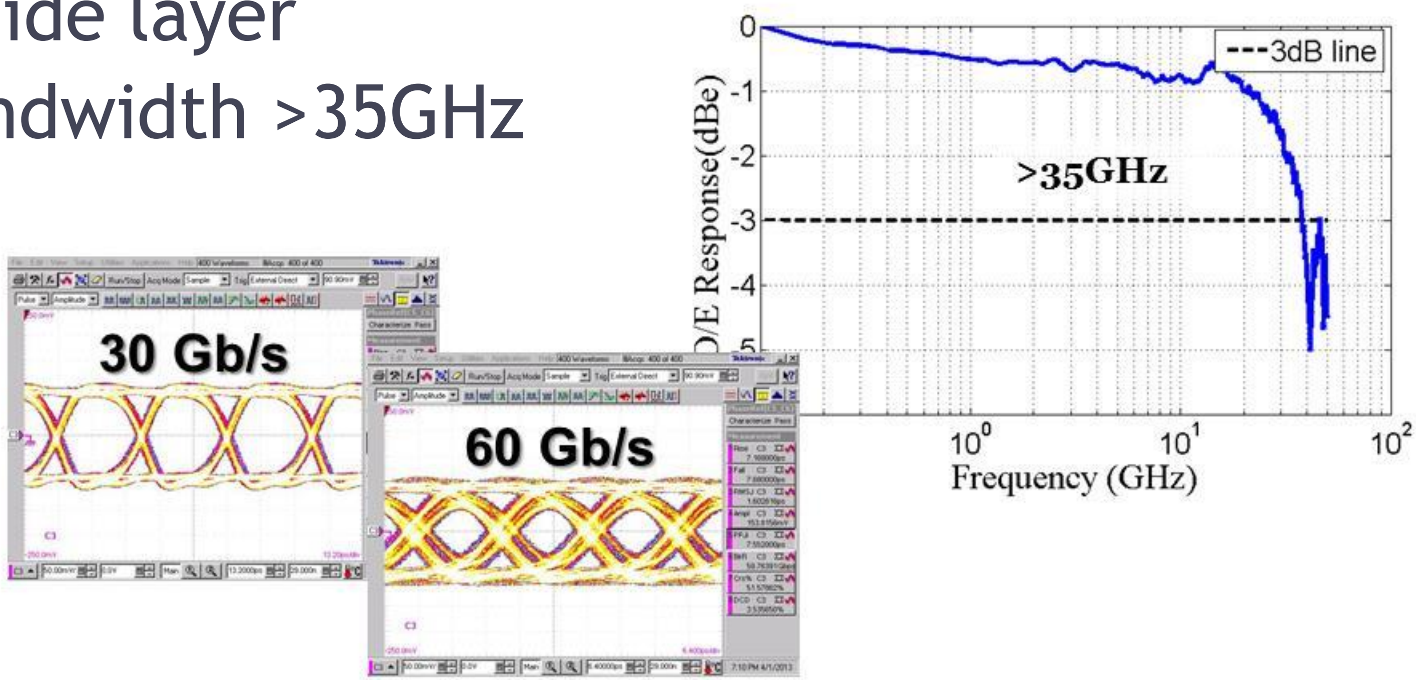
High Speed Photodiodes



- p-i-n photodiode with InGaAs absorber and Si waveguide layer
- 3dB bandwidth >35GHz



IBM/Aurrion from B.Lee et al, CLEO Postdeadline '13

aurrion

Implications for Ethernet

Silicon platform + integrated uncooled WDM…

Lowers cost of high bandwidth SMF transceivers

- 100G (4x25G –LR4, -ER4)
- 400G
  - 4x (4x25G)
  - 16x25G
  - 8x50G…

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Will Integrated Photonics take over the data center?

Daniel Mahgerefteh, *Director of Technology*

Finisar Corporation

10/15/2013

Has Photonic Integration been tested by the market?

- **InP Integration:**
- Infinera has had success here but competes on system level → not tested in the brutal, near *monopsony* of optical components market

- **Si Photonics:**
- Luxtera has had a successful product entry into Active Optical Cables → test in progress…

- Number of solutions PSM4, PAM-N, CWDM, LAN WDM looking for applications: 500-1km SMF, *LR4,and now, 300* m MMF → test not yet started…

monopsony *is a market in which only one buyer faces many sellers*

Does Integrated optics enable a Moore's law for Optics? Si Photonics example

- Three key components that are hard to shrink:

- Laser → Length~ 500 μm – 1 mm determined by InP material gain, loss, and constrained by required high output power→ unlikely to shrink by x of 2

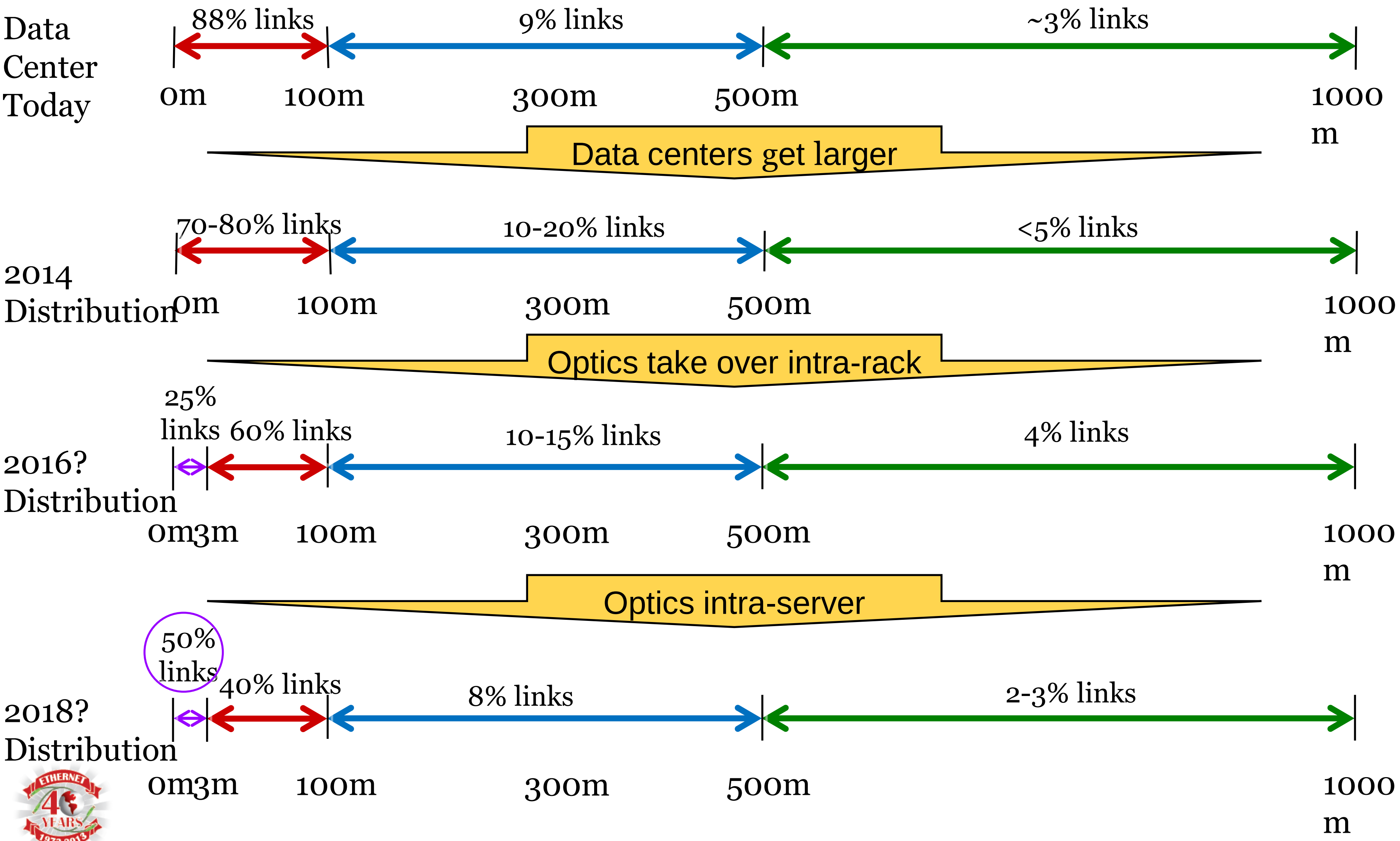
- Modulator→ Length 400 μm – 3 mm determined by weak electro-optic effect in Si → difficult to shrink by x of 2 without loss trade-off → higher laser power

- Waveguide → widths 3 μm - 0.2 μm determined by diffraction limit in Si → unlikely to shrink by x of 2. Also coupling to fiber is more difficult for smaller waveguides

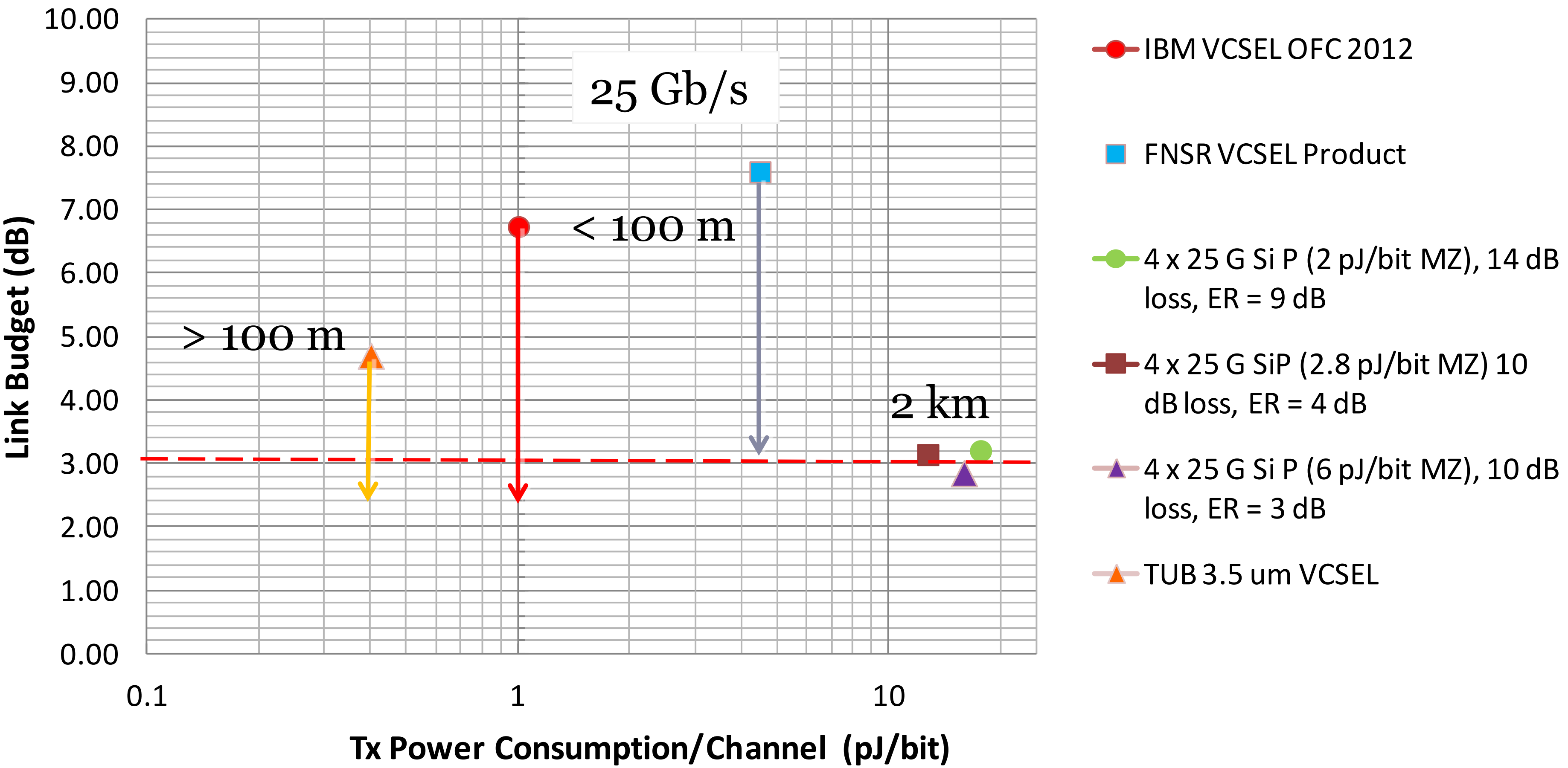
Will VCSEL products be displaced? e.g. by Si Photonics? *Highly unlikely- here's why:*

- **Si Photonics in SMF example**
- 1) Multi-Mode transceivers and board-mountable-optical assemblies (BOAs) are cheaper to manufacture due to high VCSEL yield, lower cost optics and high tolerance MM alignment
- 2) Volume for short reach MM < 100 m in data centers is over 80% of total and will continue to grow as data centers grow, and as server-to-TOR, and server-to-server interconnects evolve from electrical to optical
- 3) VCSELs have fundamentally lower power consumption (pJ/bit) for short reach MM interconnects, allowing higher density
- 4) VCSELs are smaller in size relative to InP laser + Si MZ configurations allowing higher bandwidth density

Evolution of Optical Link Length Distributions promise substantial volume growth for short reach optics



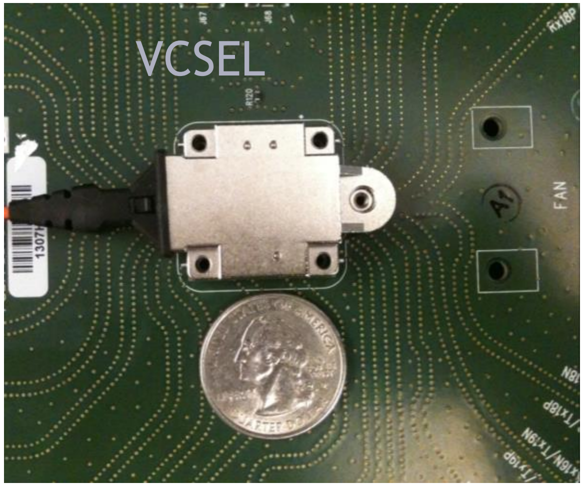
VCSEL is much more power efficient than *Lit* Si Photonics



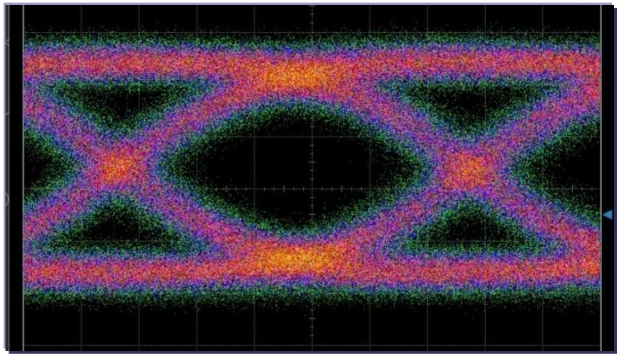
- Power consumption of VCSELs also include driver power. Power for Si Photonics includes CW laser power, and MZ driver power
- Assumed Rx sensitivity = -10 dBm for both technologies

VCSEL has 3 X higher BW density than Si Photonics today

Live Finisar OFC'13 demo



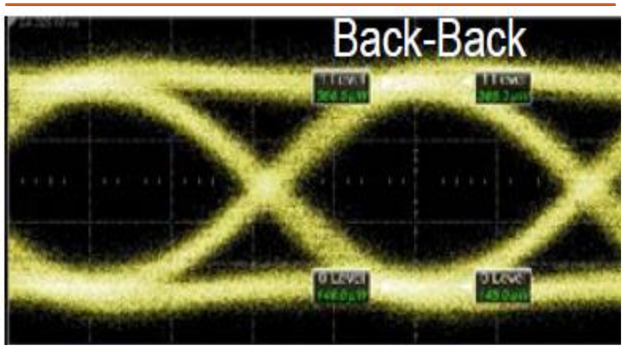
24 x 25 Gb/s Tx



600 Gb/s Tx →
3 x higher density

Intel at Open Compute

4 x 25 G Tx/Rx



4 x 25 G = 100 Gb/s

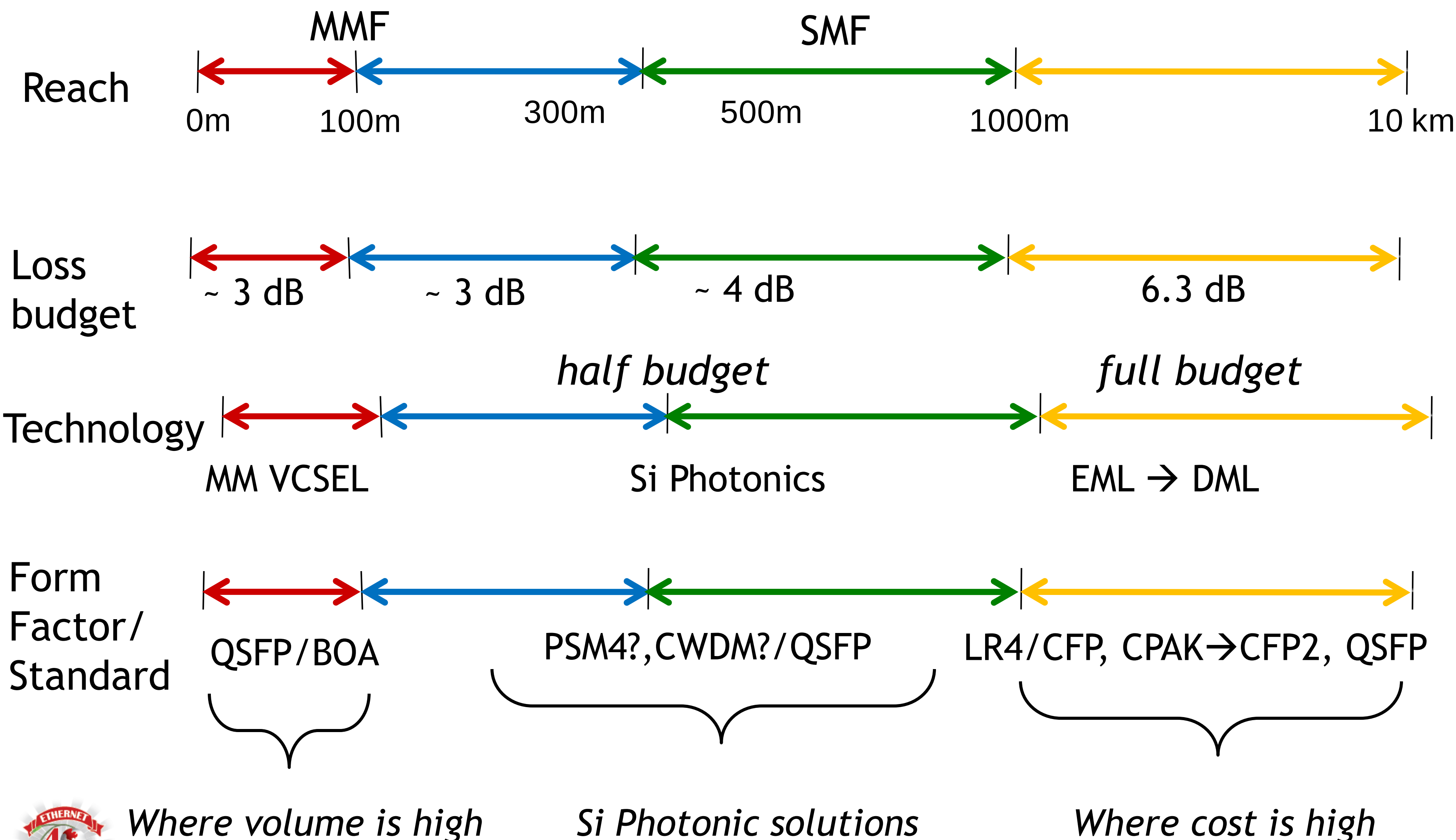
Will there be a dramatic shift to SMF?

- Majority of the market today is made up of small Enterprise datacenters, where distances are short and MMF will continue to meet the needs
- Some mega-data centers may install SMF for their infrastructure cabling, but shorter reaches remain AOC
- The overall cost of MMF solution is lower than SMF for < ~ 200 m depending on assumption of transceiver cost, and most of East-West traffic is covered by with < 100m-300 m
- Intel's 300 m Si Photonic solution uses Multi-Mode Fiber (*although it is a new fiber type*) which is a validation of lower overall cost of MMF for short reaches

Will the cost premium of SMF modules be trimmed?

- Need to specify both loss budget of optical link on SMF as well as reach before comparing costs
- LR4 supports a *full budget* 6.3 dB loss and is evolving in cost/technology/form factor from EML in CFP to DML in CFP2 or Si Photonics in CPAK → DMLs in CFP4
- Efficient, lower power DMLs are in development for the next step in LR4 evolution to QSFP28
- Alternative PSM4, CWDM, …address shorter reach and *half budget* 4 dB loss today

SMF is about *loss budget* as well as reach



Is Photonic Integration the way to achieve high density with lower power consumption?

- Integration can reduce cost for high channel counts and increase density, but *not necessarily* reduce power

- → VCSEL array 1 x to 4 x and 12 x is integration, as is N x driver, and N x TIA array
- Si Photonics also allows cost reduction and density increase by integration but does not necessarily reduce power consumption

- Power is reduced in two ways:
- 1) shortening electrical lines→ reducing needed equalization, removing CDRs: Applies to either technology

- 2) Using more efficient transmitters and more sensitive receivers → VCSELs are fundamentally lower power than Si Photonics

Which Photonic Integrated solution will win?

- VCSELs remain fundamentally lower power, and will remain lower cost for short reaches < 100 m
  - 25 G VCSELs are here!
  - Longer reaches > 300 m over standard MMF *shown to be feasible (e.g. J. S. Gustavsson OTh4H.4 OFC'13)*

- Various Si Photonic solutions are competing:
  - PMS4, CWDM, PAM-N for 4 dB loss budget @ 100G over SMF
  - Now, Hybrid 4 x 25 G Si Photonics over *new* 300 m *MM* fiber

- Directly modulated lasers remain the optimum technology for *full budget* LR4 (6.5 dB) 100 G applications
  - Efficient, lower power DMLs are in development for the next step in evolution of lower cost, lower power, smaller form factor *full budget* LR4
  - InP Integration may have a chance here

Thank you…

Technology Exploration Forum

Photonic Integration in InP for Fiber-Optics Interconnects

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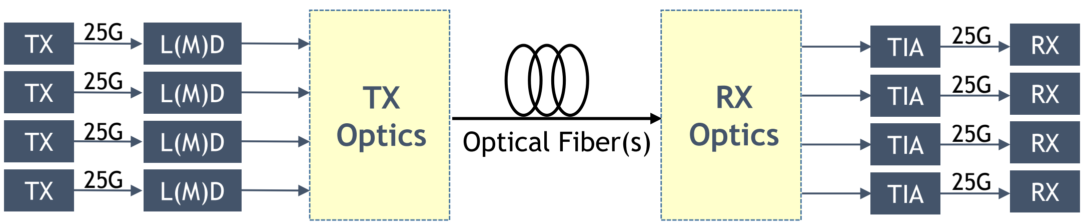
10/15/2013

Fiber-Optics Interconnects: A Problem

Simple point-to-point link architecture



- High speed (100G/OIF)
- Long reach (2km)
- High dsty (1000mm^2/100G)
- Low power (2W/100G)
- Low cost (<$500/100G)

with a set of requirements, which are difficult to meet all at once

Fiber-Optics Interconnects: Solutions

Technology	Speed	Reach	Density	Power	Cost	Comment
0.85μm VCSEL/SIPD/MMF	25G	100m				Only space-division multiplexing (parallel optics) is possible
1.31μm VCSEL/SIPD/SMF	10G	2km				O-Band VCSELs still in early stage and limited to 10G
1.31μm DFBL/SIPD/SMF	25G	40km		12W		Telco incumbents - overdesigned and overpriced
1.31μm InP PIC DFBL/WPD/SMF	25G	10km		2W		Needs cost to performance optimization
1.5Xμm SiP PIC DFBL/WPD/SMF	25G	10km		2W		Performance needs improvement; cost model questionable

VCSEL = vertical cavity surface emitting laser
SIPD = surface illuminated photodetector
MMF = multi-mode fiber

DFBL = distributed feedback laser
WPD = waveguide photodetector
SMF = single-mode fiber

On Target | Manageable | Off Target

Photonic Integration in InP

- ✓ 30 years of intense R&D, massive investment and several generations of products;
- ✓ All elements of TX / RX optics required in FOI:
  - ➢ DFB / DBR, fixed wavelength / tunable lasers
  - ➢ Electro-Absorption / Mach-Zehnder modulators
  - ➢ Waveguide PIN / avalanche broadband photodetectors
  - ➢ Arrayed waveguide grating / diffractive echelle grating filters
- ✓ But… boutique fabs, fab-specific designs and processes, many integration platforms… too fragmented;
- ✓ Paradigm change needed:
  - ➢ **from all-in-house production of one-of-a-kind PICs in low volumes at a high cost**
  - ➢ **to a fabless model based on standardized design and process building blocks, for high-volume production at the low cost.**

More often than not it is about cost

- **Optical alignment for life defined by lithography**
  - Reduces optical sub-assembly ***costs*** and increases robustness
- **Number of packaging and testing steps minimized**
  - Reduces material and overhead ***costs*** and increases robustness
- **End-to-end automation, easy volume scalability**
  - Reduces labor and production ramping up / down ***costs***
- **Small footprint size, very compact package**
  - Allows for higher packaging density, reduces line-card ***cost***

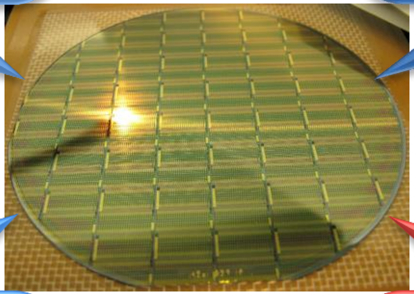
What Makes the InP PICs Cost-Efficient?

DECOUPLING OF
device and circuit designs

allows for reduction of device design & process development to those of a few generic building blocks

DECOUPLING OF
PIC design and fabrication

allows for a fabless model ops, i.e. proprietary design and outsourced fabrication (to pure play foundries)



DECOUPLING OF
epitaxy and wafer processing

allows for optimization of epi supply and wafer processing while avoiding costly (overhead & yield) regrowth

COMBINATION OF THE THREE

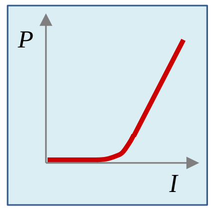
Eliminates risk of new capex
Shortens new product intro
Eases production rump up

It worked for ICs and will do for PICs

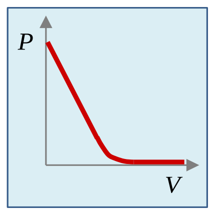
Generic Building Blocks

Active Components

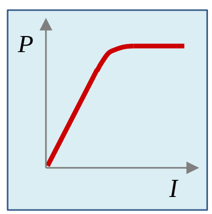
Distributed Feedback Laser



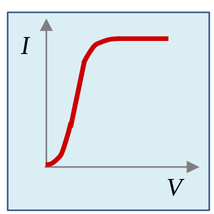
Electro-Absorption Modulator



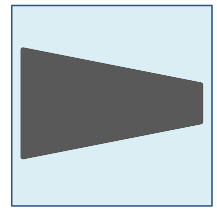
Semiconductor Optical Amplifier



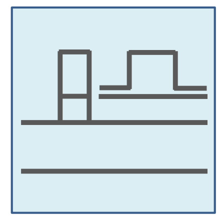
Waveguide Photodetector



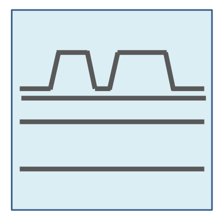
Passive Components



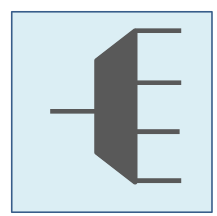
Laterally-Tapered Spot-Size Converter



Shallow / Deep Etch Ridge Waveguides

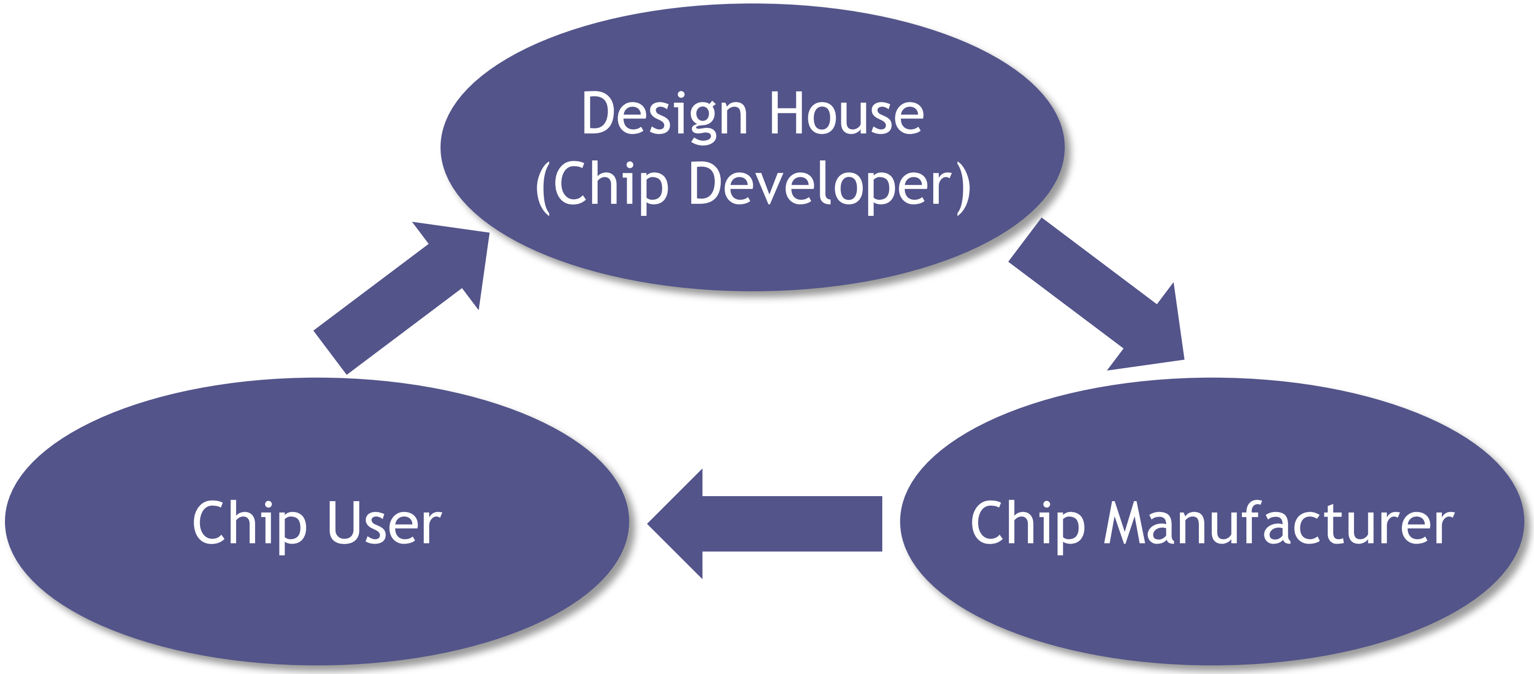


Directional Couplers / Mode Converters



Planar Wavelength Division (De)Multiplexer

Fabless Operations Model

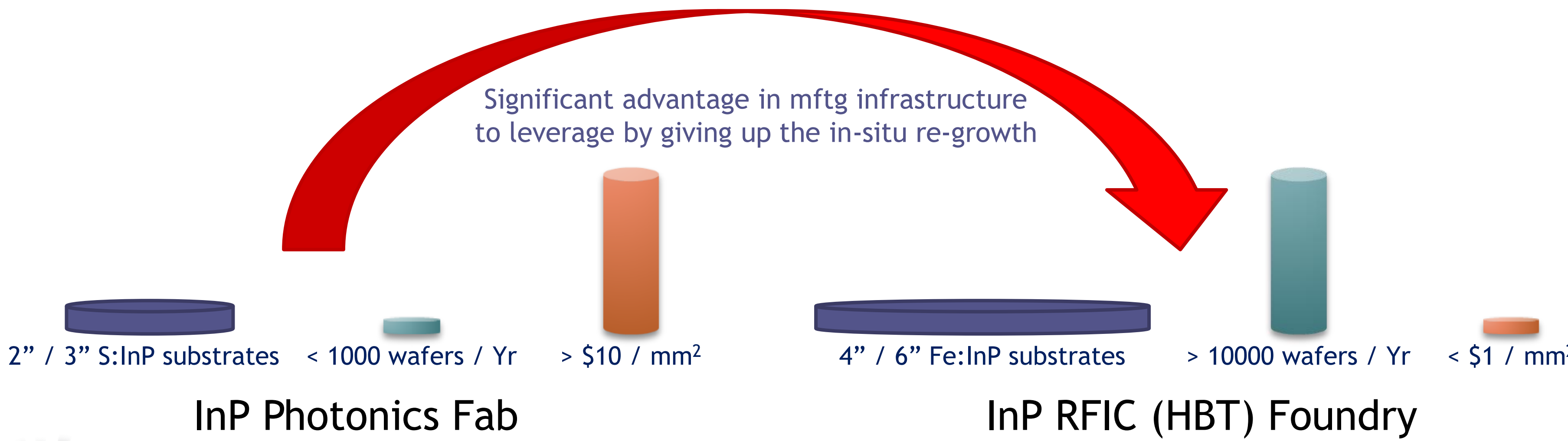


Optical sub-assembly provides (T(R)OSA)
Optical component vendors (T(R)X module)
Optical system integrators (E-O-E interface)

Pre-fab foundries (substrates, epitaxy)
Fabrication foundries (wafer processing)
Post-fab foundries (cleave/coat & dicing)

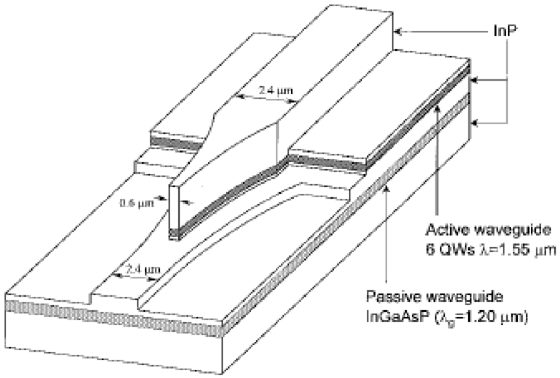
Regrowth-Free Process

- *In-situ* epitaxial re-growth adds new or replace originally grown and then etched epitaxial material in a course of wafer processing;
- Common in conventional DFBL fabrication and processing of TX PICs having such DFBLs or / and relying on butt-coupling between their actives and passives;
- Not needed for fabrication of photodetectors / sensors and RX PICs relying on evanescent-field coupling between their actives and passives;
- No re-growth used in fabrication of InP RFICs, such as HBT based power amplifiers, which absolutely dominates the overall InP production.

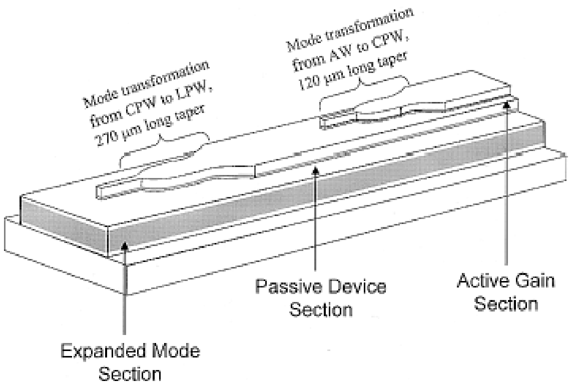


Taper Assisted Vertical Integration (TAVI)

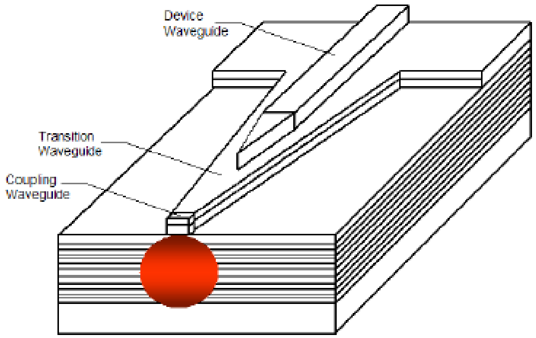
Different names, similar regrowth-free waveguide integration platforms



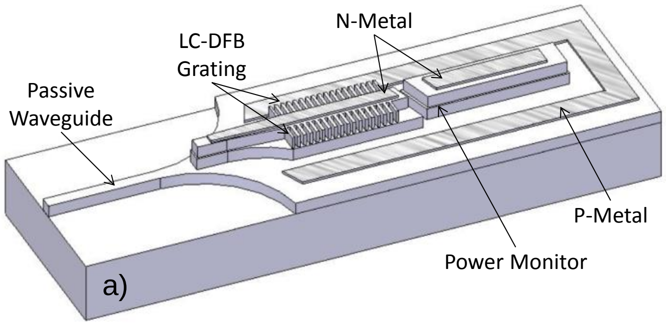
Asymmetric Twin-Waveguide (ATG) platform, *Studenkov et al, PTL 1999*



Passive-Active Resonance Coupling (PARC) platform, *Saini et al, PTL 2000*

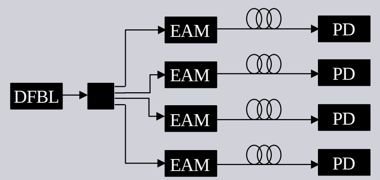
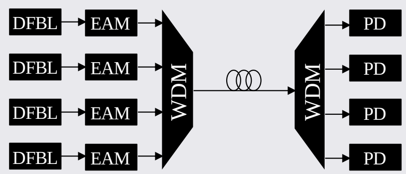
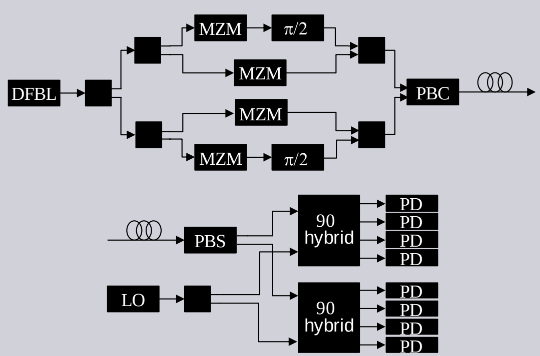


Single-Mode Vertical Integration (SMVI) platform, *Tolstikhin et al, SPIE 2004*



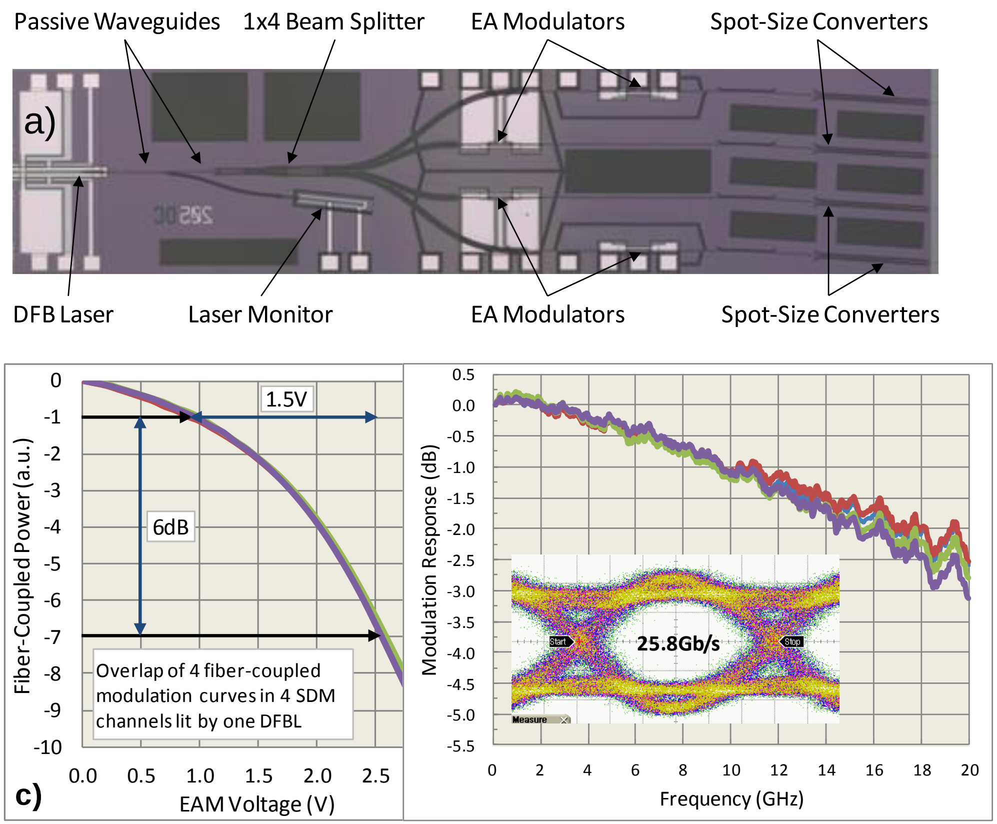
Multi-Guide Vertical Integration (MGVI) platform, *Tolstikhin et al, PTL 2009*

NG-FOI: 25G / Lane, SMF, Optical MUX

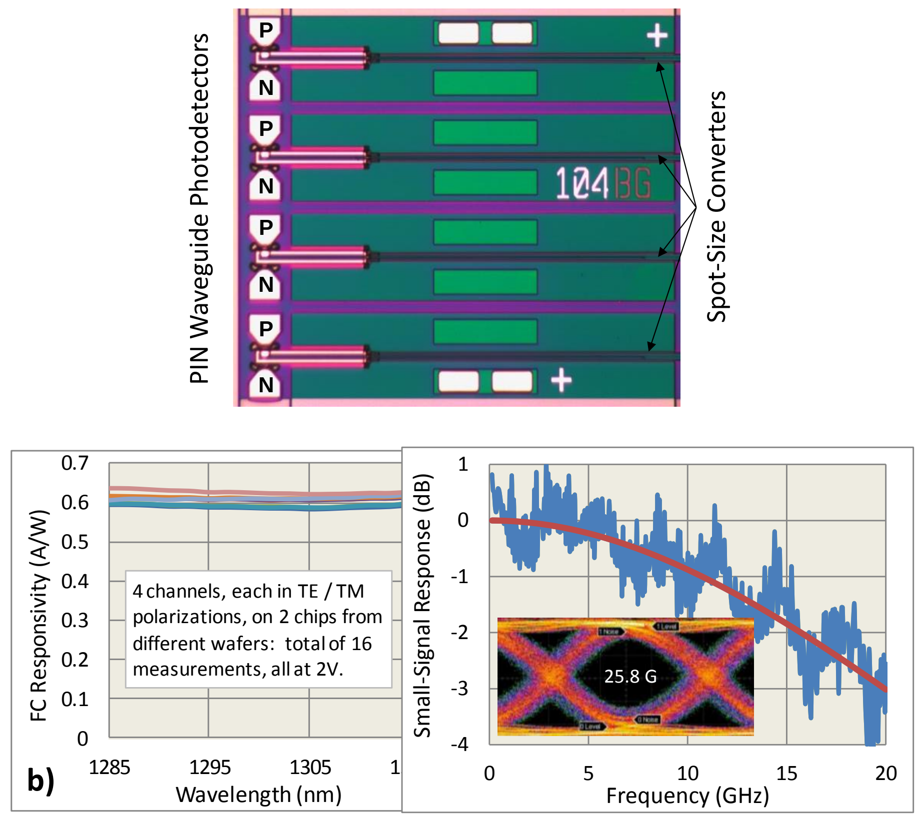
Technology	System Architecture	Pros / Cons
Space-Division Multiplexing OOK		Reduces TX laser count / minimizes cost and wall-plug power at TX end; Increases fiber count / adds to fiber cost impact on bandwidth and reach
Wavelength-Division Multiplexing OOK		Reduces the fiber count / minimizes the fiber cost impact on bandwidth and reach; Increases TX laser count / maximizes the wall-plug power at TX end
Polarization-Division Multiplexing QPSK		Increases spectral efficiency / reduces the fiber count; Complicates TX / RX optics and requires additional active (e.g. local oscillator) and passive (e.g. 90deg mixers) components, which adds on both to the cost and wall-plug power

Exemplary 4x25G SDM TAVI TX / RX PICs

4x25G SDM TX: *Tolstikhin et al, ECOC 2013, Paper P.2.20*

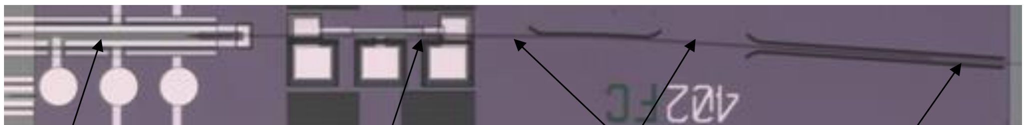


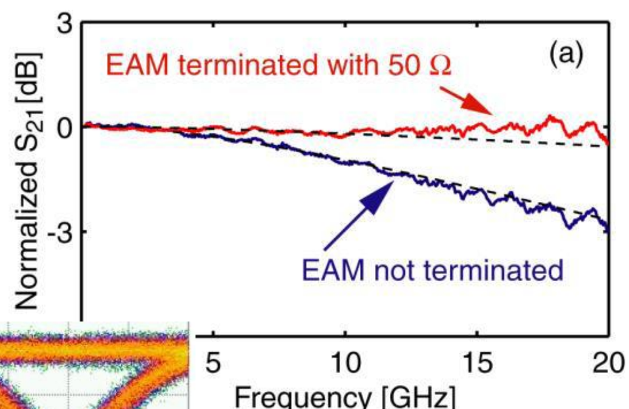
4x25G SDM RX: *Tolstikhin et al, IPR 2013, Paper IW5A.4*

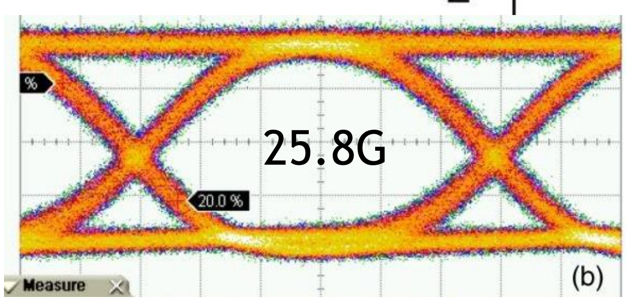


Exemplary 4x25G WDM TAVI TX / RX PICs

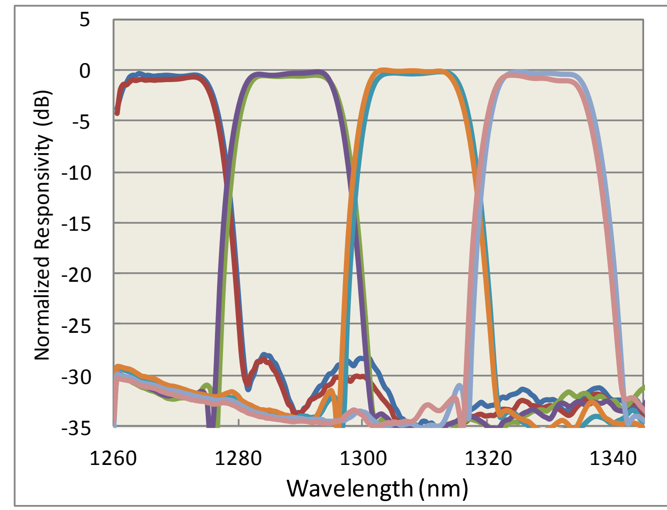
4x25G CWDM TX: *Ristic et al, IPR 2013, Paper IW5A.6*

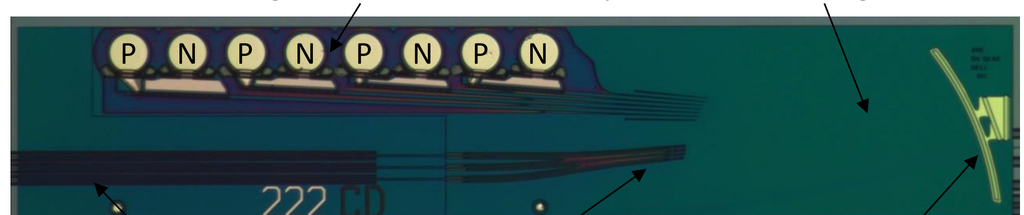






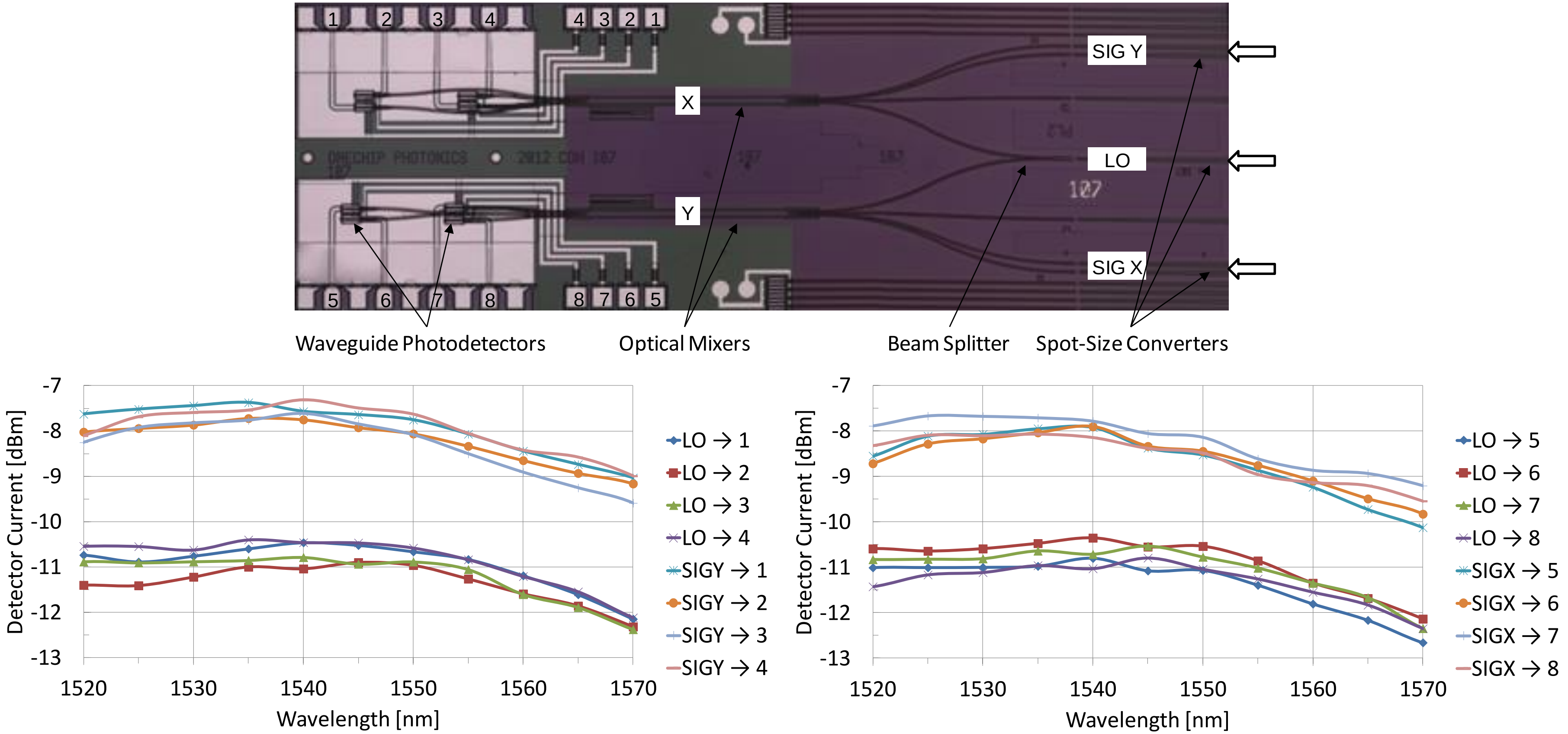
4x25G CWDM RX: *Tolstikhin et al, CLEO- 2013, Paper ThN1-3*





Exemplary 4x28G DP-QPSK TAVI RX PIC

112G (4x28G) DP-QPSK RX: *Florjanczyk et al, IPC 2013, Paper ThE2.3*



Conclusions

- Photonic integration in InP is well positioned to become an optical interface solution to next generation fiber-optics interconnects, provided it is cost-efficient;
- Fabless model, in which PIC design is based on standardized building blocks / processes while fabrication is outsourced to pure-play commercial foundries, is the path towards the required cost-efficiency in volumes for PICs, just as it was for electronic ICs;
- Whereas generic InP photonic foundry still is a long off, the InP RFIC foundries are readily available and can be utilized for fabrication of PICs compatible with the processes offered by such foundries, e.g. those not using epitaxial re-growth;
- Beyond cost-efficient PICs, InP RFIC foundries offer ready-to-go high-speed analog (HBT or p-HEMT based) electronics, which is compatible with PICs within the same process, onto one InP substrate – <u>an advancement towards OEICs</u>.