The Future of Fiber Optic Communications: Data Center & Mobile

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Acknowledgment

The insights in this presentation were gained as an employee of Finisar Corp. (acquired by II-VI Inc. in Sept. 2019) while:

- developing multiple generations of transceivers:
  10G, 25G, 40G, 50G, 100G, 200G, & 400G
- collaborating with optics industry end users, System OEMs, transceiver & component vendors, and universities

Conference Program Description

- Fiber optics are ubiquitous in cloud computing, data storage, and mobile applications, driven by demand for high-bandwidth communications. The global fiber optics market is predicted to grow to $9 billion by the end of 2025.
- The keynote will discuss trends in fiber optics for data center and mobile, including new technologies like silicon photonics (SiPh) and co-packaging. Also covered will be major technical advances in lasers, ICs, wavelength-division multiplexing (WDM), FEC, and DSP, looking in detail at two major trends: fiber optics replacing copper and coherent replacing direct detection.

Outline

- **Datacom Rates**
- Coherent in Telecom
- Coherent in Datacom
- Silicon Photonics

Datacom (Ethernet) Gb/s Data Rates vs Time

Time	Datacom (Ethernet) Gb/s MAC Rates					Rate X
1990's - 2006	0.1	1	10			10

- What's the next rate?

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1990's - 2006	0.1	1	10			10
2006 - 2007	0.1	1	10	100		10

100Gb/s vs. 40Gb/s Ethernet IEEE Debate

- 100Gb/s (4x25G) pro arguments
  - 10x is conventional rate step, fewer deployment steps for end users
  - 25GBaud NRZ technology focus will lead to lower long-term cost
- 40Gb/s (4x10G) pro arguments
  - 10GBaud technology is mature, low-risk, low-cost now
  - 40G has ~3x radix vs. 100G for 1.28T switch ASIC
    - 40Gb/s: 32x
    - 100Gb/s: 12x
  - Right server I/O step after 10Gb/s
- Both rates were adopted by the IEEE, after 40G was identified as critical to high-volume, near-term Datacenter deployment

Datacom (Ethernet) Gb/s Data Rates vs Time

Time	Datacom (Ethernet) Gb/s MAC Rates						Rate X
1990’s - 2006	0.1	1	10				10
2006 - 2007	0.1	1	10	100			10
2008 - 2013	1		10	40	100		~2 or 4

- What’s the next rate?

Datacom (Ethernet) Gb/s Data Rates vs Time

Time	Datacom (Ethernet) Gb/s MAC Rates						Rate X
1990's - 2006	0.1	1	10				10
2006 - 2007	0.1	1	10	100			10
2008 - 2013	1		10	40	100		4
2014 - 2015	1		10	40	100	400	4

400Gb/s vs. 200Gb/s Ethernet IEEE Debate

- 400Gb/s (4x100G) pro arguments
  - 4x is <u>conventional</u> rate step, fewer deployment steps
  - 100GBaud PAM-4 technology focus: lower long-term cost
- 200Gb/s (4x50G) pro arguments
  - 25GBaud technology is mature, low-risk, low-cost now
  - 200G has 2x radix vs. 400G for 12.8T switch ASIC
    - 200Gb/s: 64x (or for 100Gb/s: 128x)
    - 400Gb/s: 32x
  - Right server I/O step after 100Gb/s
- Both rates were adopted by the IEEE after 200G was identified as important for Mobile applications in China

The Big Four Plans - 2019

- AWS
  - 400G DR4 broken out to four 100GbE
- Google
  - Shifting from 100GbE to 200GbE in the form of 2x200G modules
  - 2x400G modules the next step
- Facebook
  - New high-density 100GbE switch fabric for 4X capacity
  - 200GbE the next step
- Microsoft
  - Will deploy 400GbE inside data centers after 400ZR availability
- No clear plans to deploy 400GbE for some time!

LightCounting High-Speed Ethernet Optics Report – April 2019 – page 12

Why no near-term 400GbE plans?

- Still rather early in the 100GbE life cycle
- 12.8Tb switches provide only 32 ports of 400GbE
- Cannot scale a switch fabric with just 32 ports
- No practical means to build a 128-port 400GbE switch such as Facebook and Arista have announced
- Concerns about availability of 400G optical modules
- Expectation that switches and modules with 100Gb/s SerDes will result in efficient and economical 400GbE

LightCounting High-Speed Ethernet Optics Report – April 2019 – page 13

Next High-Volume Ethernet Data Rate

- Huge industry investment into 1st Gen 400GbE (with great expectation that this will be the next high-volume Datacom rate) will have no ROI
- 1st Gen 400GbE optics are small volume, primarily for Telecom
- 200GbE is the next high-volume Datacom rate
- Common characterization of 200GbE as an “interim” step to 400GbE is just like the characterization of 40GbE as an “interim” step to 100GbE
- 400GbE will be high volume when following are mature:
  - 100Gb/s lane SerDes
  - 7nm CMOS PHYs
  - TX and RX 56GBaud optics have excess bandwidth

Datacom (Ethernet) 1st Million Units Shipped Milestones

Years shipped after IEEE 802.3 Standard publication of 1st million units :

- 10GbE 6 (2008)
- 40GbE 4 (2014)
- 100GbE* 6 (2016)
- 200GbE 4 (2021, predicted)
- 400GbE* 6 (2023, predicted)

*4 years from 802.3 Standard development start to publication

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1990's - 2006	0.1	1	10						10
2006 - 2007	0.1	1	10		100				10
2008 - 2013	1		10		40	100			4
2014 - 2015	1		10		40	100	400		4
2016 to today	2.5	5	10	25	40/50	100	200	400	2

- What's the next rate?

1.6Tb/s vs. 800Gb/s Ethernet IEEE Debate

- 1.6TGb/s pro arguments
  - 4x is conventional rate step, fewer deployment steps
  - 800GbE is an “interim” step to 1.6TbE
- 800Gb/s pro arguments
  - 100GBaud PAM4 technology will be mature, low-risk, low-cost
  - 800GbE has 2x radix vs. 1.6TbE
- Why 1.6TbE?
- Same obsession with bandwidth that drove 100GbE and 400GbE
- Same fantasies about shipment volumes as for 100GbE and 400GbE

  Example: IEEE NEA 802.3 Ad Hoc meeting, 21 Jan 2020, report from Dell’Oro Group, using “actual data”, forecasts 1st million 400GbE by 2020

Datacom (Ethernet) Gb/s Data Rates vs Time Prediction

Datacom (Ethernet) Gb/s MAC Rates						
25	50	100	200	400	800	1600

- IEEE will split the baby and adopt both 800GbE and 1.6TbE rates
- Suppliers will develop 1st Gen 1.6TbE transceivers which will have no ROI
- 1st million units shipped:
  - 800GbE: 2028
  - 1.6TbE: 2030

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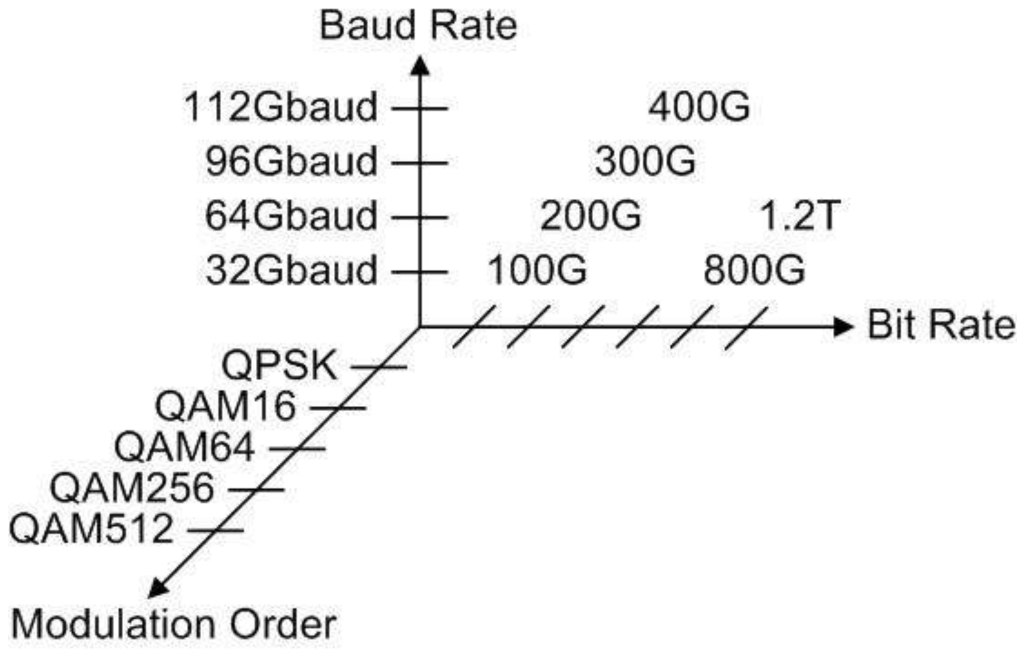
Telecom Today

- Installed fiber has been the Network capacity constraint
- Increasing Spectral Efficiency (SE) of the fiber has been the R&D focus
- SE increase techniques:
    - DSP/CMOS
    - Coherent, SD-FEC
    - Spectral shaping, Dense DWDM
    - Flex-Grid, Flex-Ethernet
    - Super-channels
- What's next?
- Conventional thinking says increase
  Bit Rate, GBaud, and Mod. order
- Shannon limit and escalating cost means meager SE gains



Shannon-Hartley Theorem

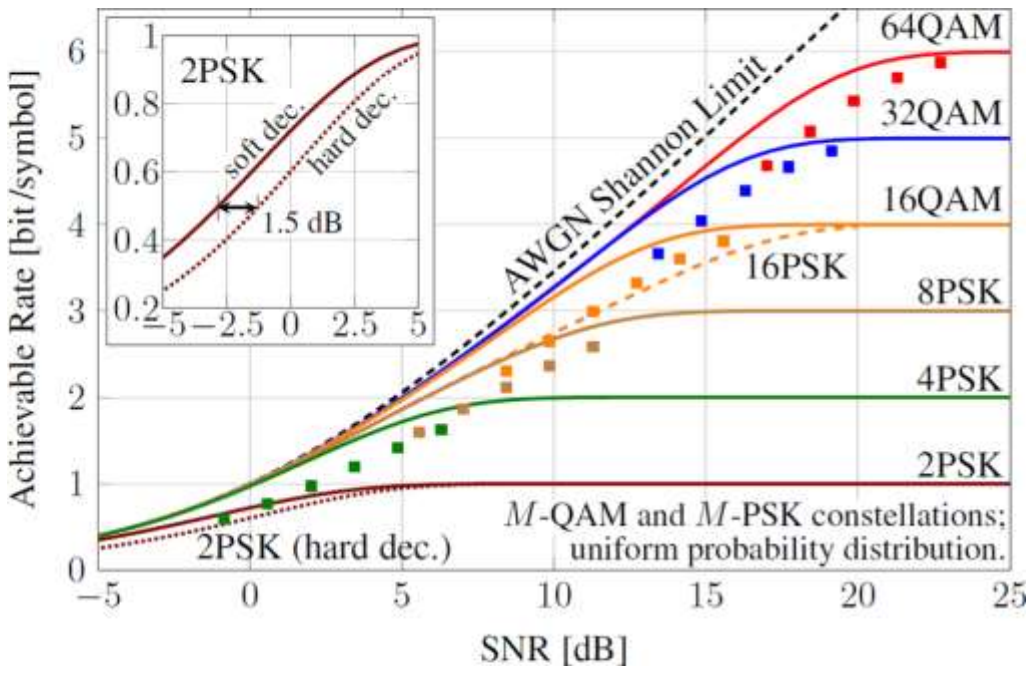
$C = BW \log_2(1 + S/N)$

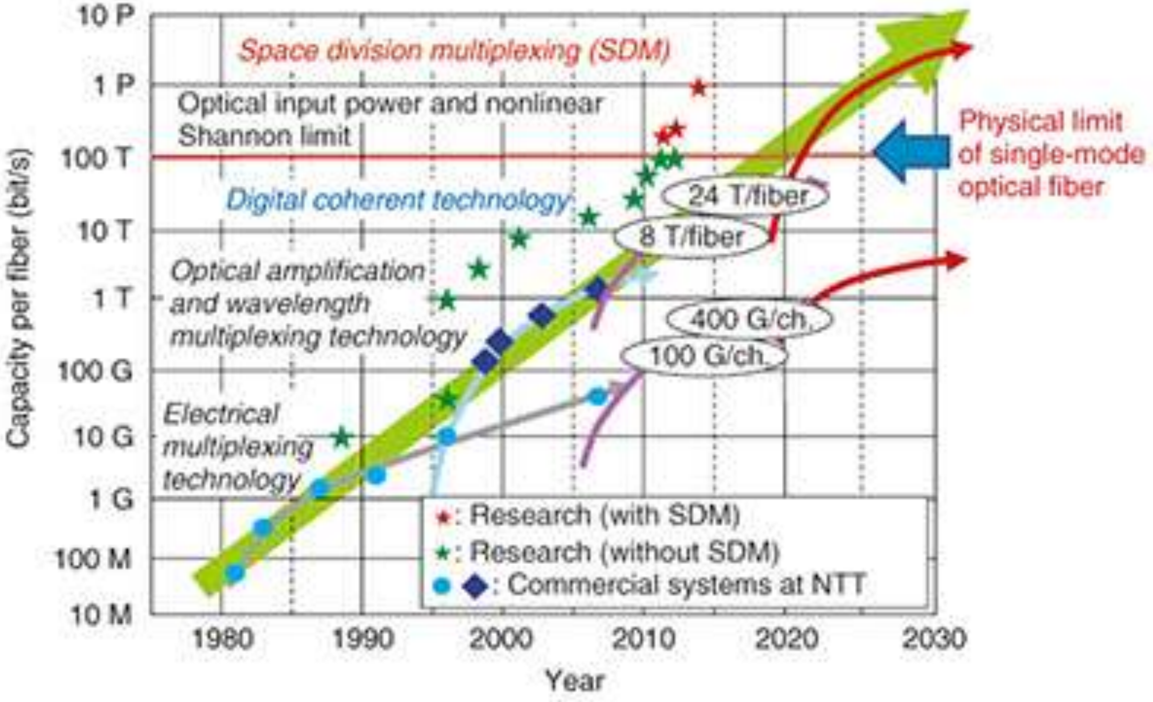
C	≜ Channel Capacity
BW	≜ Bandwidth
S	≜ Signal Power
N	≜ Noise Power

Guidance to increase C:

- S/N limited: increase BW to support higher Baud rate, ex. Datacom
- BW limited: increase S/N to support higher order modulation, ex. Telecom
- If both BW and S/N limited, increase channels, i.e. parallel fiber

Fundamental Limits





Telecom Tomorrow

- Installed fiber is reaching full utilization
- New fiber will have to be installed to increase capacity
- Cost is dominated by installation, while the cost of fiber is minor
- Cost to install massive amount of fiber, most of which is initially unused, is same as installing only what's needed
- Spectral Efficiency is a minor performance metric when fiber is plentiful
- What's next?
- Per λ bit rate, GBaud, Mod. order will be reduced to enable cheap, massively parallel optics
- This is the opposite of current R&D focus, … and conventional thinking

Telecom Prediction

- 100G Coherent will dominate Long Haul
- 400G Coherent (i.e. ZR) will dominate Metro
- There will be no price premium on performance
- It will be all about low cost just like in Datacom, i.e. ugly
- At least the construction and fiber guys will make money … for a while

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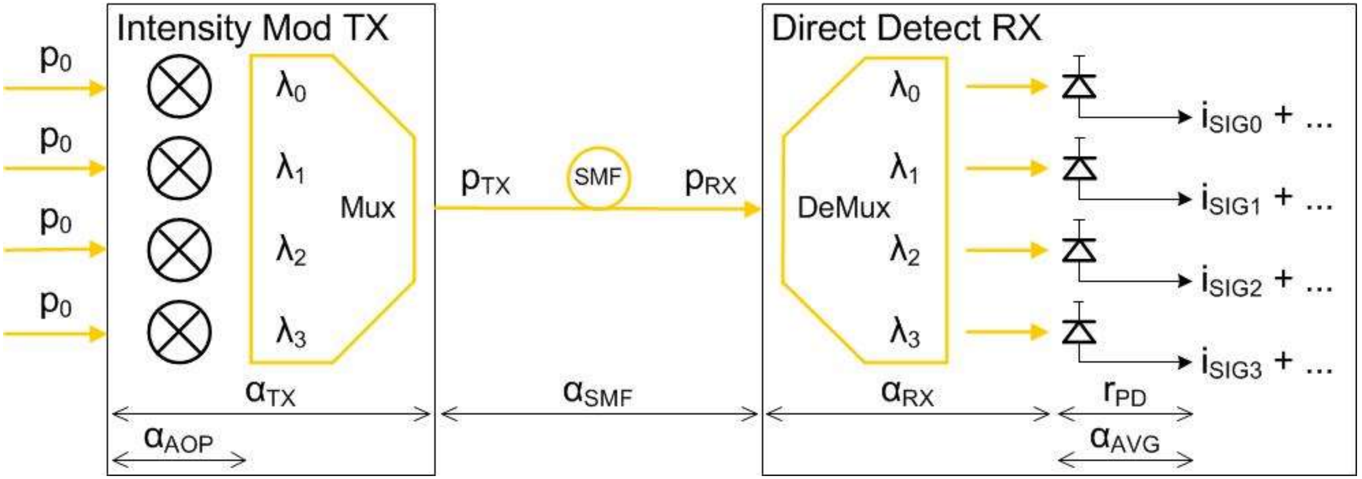
IMDD vs. Coherent in the Datacenter Debate

- 10G/λ and slower rate Transport was IMDD
  (Intensity Modulation Direct Detection)
- 40G/λ Transport was transitional
- 100G/λ and faster rate Transport is Coherent
  - SNR increase
  - Fiber impairment compensation
  - Link adaptation
- Conventional thinking is that Coherent will replace IMDD for Datacom links inside the datacenter, just like it replaced IMDD for Telecom links

CWDM4 1km SMF Spec Limits

- L0 λ: 1271nm, λ_{min} = 1264.5nm w/ $\lambda_{zero\_dispersion\_max}$ = 1324nm
  - Dispersion = -6 ps/nm
  - PMD = 0.5 ps
  - Loss = 0.47dB
- L3 λ: 1331nm, λ_{max} = 1337.5nm w/ $\lambda_{zero\_dispersion\_min}$ = 1304nm
  - Dispersion = 3 ps/nm
  - PMD = 0.5 ps
  - Loss = 0.43dB
- Inside the Datacenter, fiber impairments and variability are not important
- TX, Link (SMF, connectors, passives) and RX loss drives SNR and design

Direct Detection (DD) Signal Path



$p_{IN\text{-}TX} = 4\, p_0$

$p_{TX} = \alpha_{TX}\, \alpha_{AOP}\, p_{IN\text{-}TX}$

$i_{SIG} = \alpha_{AVG}\, r_{PD}\, p_{PD}$

$p_{RX} = \alpha_{SMF}\, p_{TX}$

$p_{PD} = \alpha_{RX}\, p_{RX} / 4$

Direct Detection (DD) Signal Path Variables

$p_0 \triangleq$ Input POP (Peak Optical Power) reference

$p_{IN\text{-}TX} \triangleq$ TX input POP = AOP (Average OP) if CW

$\alpha_{AOP} \triangleq$ TX POP to AOP modulation loss vs. er (extinction ratio)

$\alpha_{TX} \triangleq$ TX path intrinsic loss at modulator bias point

$p_{TX} \triangleq$ TX total output AOP

$\alpha_{SMF} \triangleq$ Link total power loss (connectors, SMF, other passives)

$p_{RX} \triangleq$ RX total input AOP

$\alpha_{RX} \triangleq$ RX path intrinsic loss

p_{PD}, $r_{PD} \triangleq$ RX PD input AOP, responsivity

$\alpha_{AVG} \triangleq$ PD AOP to average electrical signal power loss vs. er

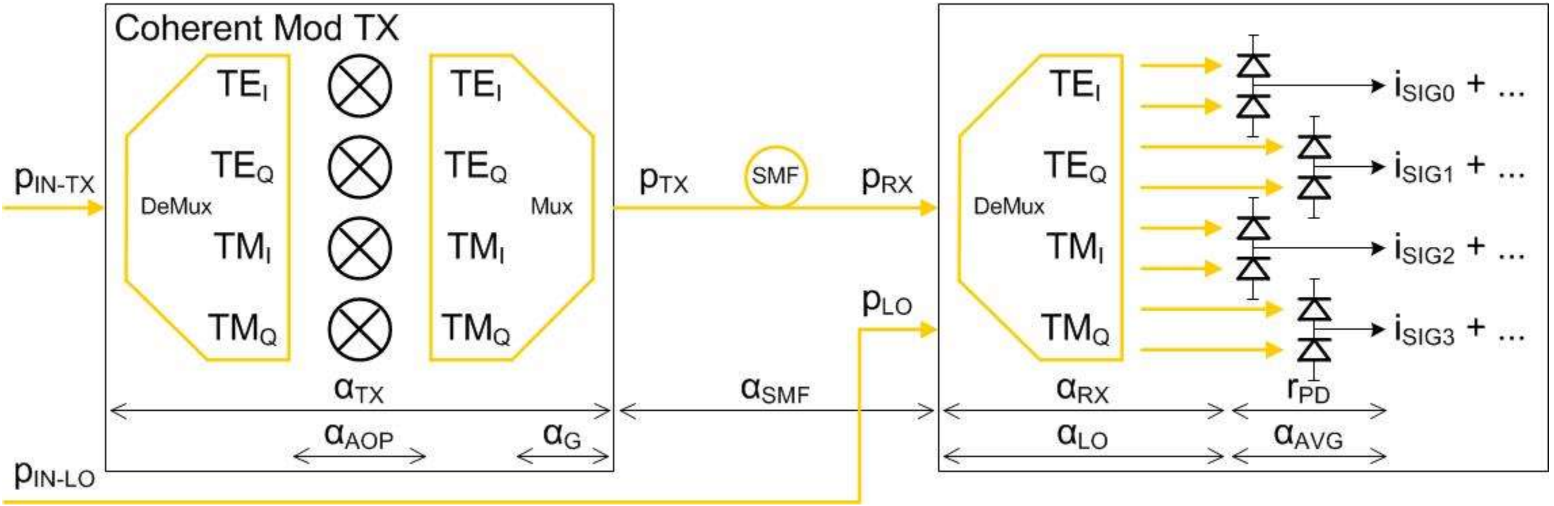
Direct Detection (DD) SNR

$i_{SIG} \triangleq$ RX PD signal current
$i_{SIG} = \alpha_{AVG}\, r_{PD}\, p_{PD} = \alpha_{AVG}\, \alpha_{RX}\, \alpha_{SMF}\, \alpha_{TX}\, \alpha_{AOP}\, r_{PD}\, p_0$

$i_N \triangleq$ RX input referred noise current; all sources
$\alpha_N \triangleq$ RX input noise current loss vs. reference
i_{ND}, i_0, BW $\triangleq$ RX input noise current density, reference, bandwidth
$i_N = i_{ND} \sqrt{BW}$
$i_{ND} = \alpha_N\, i_0$
$i_N = \alpha_N\, i_0 \sqrt{BW}$

$snr = (i_{SIG} / i_N)^2$
$\sqrt{snr} = \alpha_{AVG}\, \alpha_{RX}\, \alpha_{SMF}\, \alpha_{TX}\, \alpha_{AOP}\, r_{PD}\, p_0 / (\alpha_N\, i_0 \sqrt{BW})$

Coherent (CH) Signal Path



$p_{IN\text{-}TX} = 4\ \alpha_{LS}\ \alpha_{TEC}\ p_0$

$p_{TX} = \alpha_G\ \alpha_{TX}\ \alpha_{AOP}\ p_{IN\text{-}TX}$

$p_{IN\text{-}LO} = 4\ (1 - \alpha_{LS})\ \alpha_{TEC}\ p_0$

$p_{RX} = \alpha_{SMF}\ \alpha_{TX}$

$p_{PD\text{-}RX} = \alpha_{RX}\ p_{RX} / 4$

$p_{LO} = p_{IN\text{-}LO}$

$p_{PD\text{-}LO} = \alpha_{LO}\ p_{LO} / 4$

$i_{SIG} = \alpha_{AVG}\ r_{PD}\ 2\ \sqrt{(p_{PD\text{-}RX}\ p_{PD\text{-}LO})}$

Coherent (CH) Signal Path Variables

$p_0 \triangleq$ Input POP (Peak Optical Power) reference
$\alpha_{TEC} \triangleq$ Input POP loss due to laser TEC current
$\alpha_{LS} \triangleq$ TX input POP loss due to (1- α_{LS}) split with LO input
$p_{IN\text{-}TX} \triangleq$ TX input POP = AOP since CW
$\alpha_{AOP} \triangleq$ TX POP to AOP modulation loss vs. MD (mod. drive)
$\alpha_{TX} \triangleq$ TX path intrinsic loss at modulator bias point
$\alpha_G \triangleq$ TX optical gain (α_G = 1 if no amplification)
$p_{TX} \triangleq$ TX total output AOP
$\alpha_{SMF} \triangleq$ Link total power loss (connectors, SMF, other passives)

Coherent (CH) Signal Path Variables, cont.

p_{RX} ≜ RX total input AOP
p_{LO} ≜ RX LO input AOP
α_{RX}, α_{LO} ≜ RX, RX LO path intrinsic loss
$p_{PD,}$ r_{PD} ≜ RX balanced PD pair input AOP, responsivity
α_{AVG} ≜ PD AOP to average electrical signal power loss vs. MD

Coherent (CH) SNR

$i_{SIG} \triangleq$ RX balanced PD pair signal current
$i_{SIG} = \alpha_{AVG}\, r_{PD}\, 2 \sqrt{(p_{PD\text{-}RX}\, p_{PD\text{-}LO})} \cos(\Phi)$
$\cos(\Phi) \triangleq 1,\ \ \alpha_{LS} \triangleq 1/2,\ \ \alpha_{LO} \triangleq \alpha_{RX}$
$i_{SIG} = \alpha_{AVG}\, \alpha_{RX} \sqrt{(\alpha_{SMF}\, \alpha_{G}\, \alpha_{TX}\, \alpha_{AOP})}\, \alpha_{TEC}\, r_{PD}\, p_0$

$i_N \triangleq$ RX input referred noise current; all sources
$\alpha_N \triangleq$ RX input noise current loss vs. reference
i_{ND}, i_0, BW $\triangleq$ RX input noise current density, reference, bandwidth
$i_{ND} = \alpha_N\, i_0$
$i_N = \alpha_N\, i_0 \sqrt{BW}$

$snr = (i_{SIG} / i_N)^2$
$\sqrt{snr} = \alpha_{AVG}\, \alpha_{RX} \sqrt{(\alpha_{SMF}\, \alpha_{G}\, \alpha_{TX}\, \alpha_{AOP})}\, \alpha_{TEC}\, r_{PD}\, p_0 / (\alpha_N\, i_0 \sqrt{BW})$

$\sqrt{(snr_{DD} / snr_{CH})}$

$\sqrt{snr_{DD}} = \alpha_{AVG}\, \alpha_{RX}\, \alpha_{SMF}\, \alpha_{TX}\, \alpha_{AOP}\, r_{PD}\, p_0 / (\alpha_N\, i_0\, \sqrt{BW})$

$\sqrt{snr_{CH}} = \alpha_{AVG}\, \alpha_{RX}\, \sqrt{(\alpha_{SMF}\, \alpha_G\, \alpha_{TX}\, \alpha_{AOP})}\, \alpha_{TEC}\, r_{PD}\, p_0 / (\alpha_N\, i_0\, \sqrt{BW})$

$r_{PD\text{-}DD} \triangleq r_{PD\text{-}CH}$

$BW_{DD} \triangleq BW_{CH}$

$$\sqrt{(snr_{DD} / snr_{CH})} = \alpha_{AVG\text{-}DD}\, \alpha_{RX\text{-}DD}\, \alpha_{SMF}\, \alpha_{TX\text{-}DD}\, \alpha_{AOP\text{-}DD}\, \alpha_{N\text{-}CH} / \alpha_{AVG\text{-}CH}\, \alpha_{RX\text{-}CH}\, \sqrt{(\alpha_{SMF}\, \alpha_G\, \alpha_{TX\text{-}CH}\, \alpha_{AOP\text{-}CH})}\, \alpha_{TEC}\, \alpha_{N\text{-}DD}$$

$$\Delta SNR_{DD\text{-}CH} = SNR_{DD} - SNR_{CH} \text{ dB}$$

$A \triangleq$ loss in optical -dB

$A = -10\log_{10}(\alpha)$

$\Delta SNR_{DD\text{-}CH} = SNR_{DD} - SNR_{CH} = 10\log_{10}(snr_{DD} / snr_{CH})$

$$\begin{aligned}\Delta SNR_{DD\text{-}CH} / 2 = &- (A_{AOP\text{-}DD} + A_{TX\text{-}DD} + A_{SMF}) \\ &+ (A_{AOP\text{-}CH} + A_{TX\text{-}CH} + A_{G} + A_{SMF}) / 2 + A_{TEC} \\ &- (A_{AVG\text{-}DD} + A_{RX\text{-}DD} - A_{N\text{-}DD}) \\ &+ (A_{AVG\text{-}CH} + A_{RX\text{-}CH} - A_{N\text{-}CH})\end{aligned}$$

$\Delta SNR_{DD\text{-}CH}$ dB Examples, 4dB SMF Link

$\Delta SNR_{DD\text{-}CH}$ dB		Scenario	1. Equal laser DC power		2. Equal total input AOP		3. Equal TX output AOP	
Ex. #	TX & RX Implementation		NRZ - QPSK	PAM4 - QAM16	NRZ - QPSK	PAM4 - QAM16	NRZ - QPSK	PAM4 - QAM16
1	Ideal TX & RX no loss DD ER = ∞, CH MD = V_π		5.4		-2.6		-5.6	-8.1
2	DD CWDM4 TFF DML TX ER = 4.8, SiP CH MD = V_π		15.4		7.4		-8.6	-11.1
3	DD CWDM4 TFF EML TX ER = 7, SiP CH MD = V_π		11.5		3.5		-9.3	-11.8
4	DD PSM4 SiP TX ER = 7, SiP CH MD = V_π		9.5		1.5		-10.3	-12.8
5	DD CWDM4 SiP TX ER = 7, SiP CH MD = V_π		1.5		-6.5		-16.3	-18.8

Coherent vs. IMDD SNR Relations

Application	Direct Detection NRZ / PAM4 SNR		SNR Relation	Coherent QPSK / QAM16 SNR	
	TX	RX		TX	RX
Laser DC Power Constrained 4dB Link Loss	EML, DML single λ or TFF, PLC WDM	PIN single λ or TFF, PLC WDM	>>	SiP	SiP
	single λ SiP (PSM)	single λ SiP (PSM)	>>	SiP	SiP
	WDM SiP	WDM SiP	≈	SiP	SiP
TX Out Power Constrained	Any	PIN	<<	SiP	SiP

- For most datacenter links, IMDD has better SNR than Coherent, contrary to conventional wisdom

Mini Boot Camp - Is Coherent Right For You?

L_{Path} ≜ Loss of Path in optical dB
$L_{LSR\_to\_P\_Diode} = L_{TX} + L_{Link} + L_{RX}$
$\Delta SNR_{DD\text{-}CH} = SNR_{DD} - SNR_{CH}$ (SNR, Direct Detection - Coherent)
Scenario 2 = Equal Laser Power (TEC$_{CH}$ current not included, p.36)

$$\Delta SNR_{DD\text{-}CH} \approx (L_{TX\text{-}CH} + L_{Link\text{-}CH} + 2L_{RX\text{-}CH}) - 2(L_{TX\text{-}DD} + L_{Link\text{-}DD} + L_{RX\text{-}DD})$$

- 100G DML NRZ CWDM4 vs. 100G SiPh QPSK Coherent (Ex. 2 on p.36)
  $\Delta SNR_{DD\text{-}CH} \approx (17 + 4 + 12.5) - 2(4 + 4 + 5) = 7.5\text{dB}$
- 100G DML NRZ CWDM4 vs. 100G SiPh QPSK Coherent + 12dB OC switch
  $\Delta SNR_{DD\text{-}CH} \approx (17 + (4 + 12) + 12.5) - 2(4 + (4 + 12) + 5) = -4.5\text{dB}$
  (16dB is the same loss as 40km of SMF, i.e. like a Metro link)

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Datacenter and Silicon Photonics (SiPh)

- What’s important for Datacenter optics
  - Cheap laser(s)
  - Cheap SNR (low loss)
  - Cheap assembly and packaging

- How does SiPh stack-up?
  - Si is an indirect band-gap semiconductor, so it’s a lousy light amplifier
  - Si therefore makes a lousy LASER (LA stands for Light Amplification)
  - SiPh has higher loss than other technologies like free space optics
  - SiPh packaging is comparable in cost to conventional packaging

Silicon Photonics Myth 1

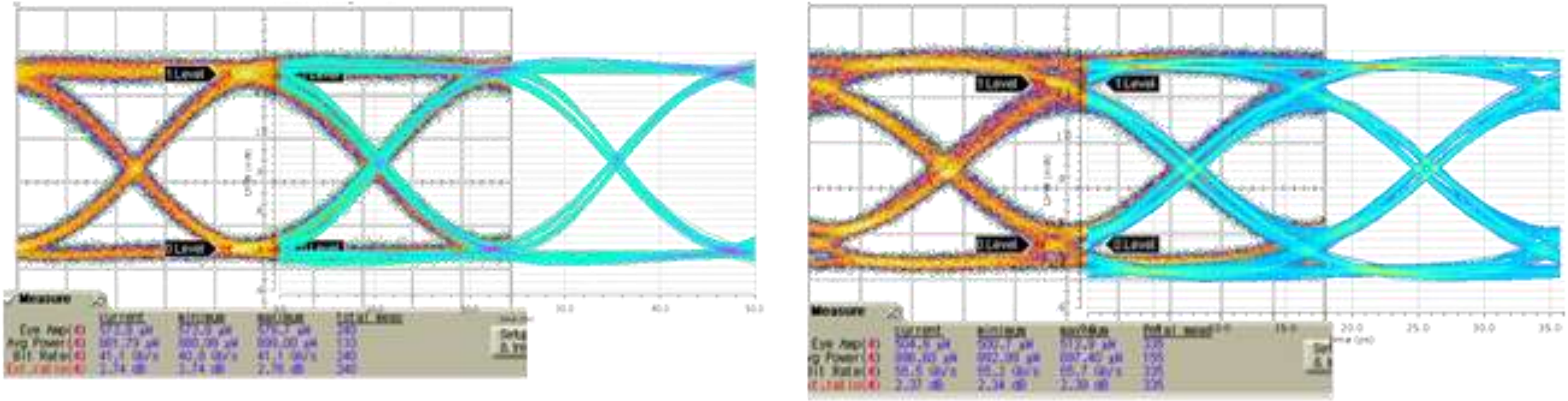
- SiPh is low cost
  - SiPh is expensive when all costs are properly accounted for
  - This includes process development, components development, modelling, masks, testing, yield improvement, and others
  - SiPh to have decent cost, requires very high yield of SiPIC, process steps, and integrated assembly
  - There are many yield pitfalls, just like in conventional optics
- Why the myth?
  - SiPh has inferior performance to conventional datacom transceivers
  - If you can’t sell on value, sell on price
  - Low cost is the only marketing claim that can be made

Silicon Photonics Myth 2

- SiPh design is like CMOS ASICs
  - The two largest ASIC CAE companies (Synopsys and Cadence) have similar revenue (~$5.5B) to the entire Datacom optics industry
  - The true cost of developing just PDKs for advanced CMOS nodes is comparable to the entire R&D budget of an optical transceiver vendor
  - CMOS tool predictability results in first pass success of complex ASICs
- SiPh tools do not predict final product performance
- Assembled and packaged SiPh performance is not modelled
- Any successful design effort requires device and process engineers

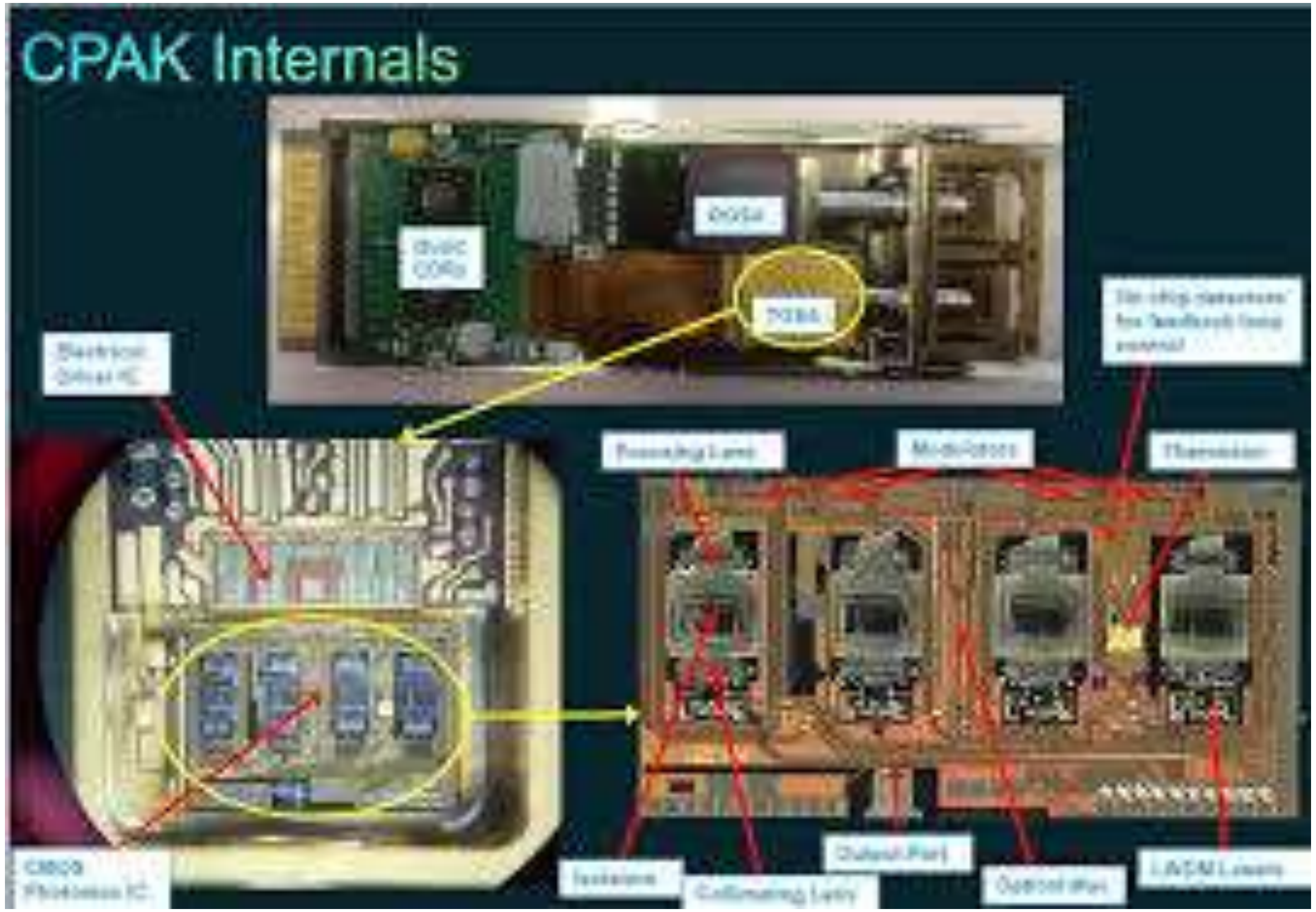
Silicon Photonics Myth 2 Counter Point

- With proper investment and effort, SiPh Tools can give good results
- 40Gb/s and 56Gb/s TX eyes, Finisar 400G DR4 prototype SiPIC, 2014



G. Denoyer, C. Cole, et al., "Hybrid Silicon Photonics Circuits and Transceiver for 50Gb/s NRZ Transmission Over Single-Mode Fiber, Journal of Lightwave Technology, vol. 33, no. 6, 15 Mar. 2015.

Cisco Lightwire 100G LR4 CPAK



Luxtera PSM4 SiPh QSFP28

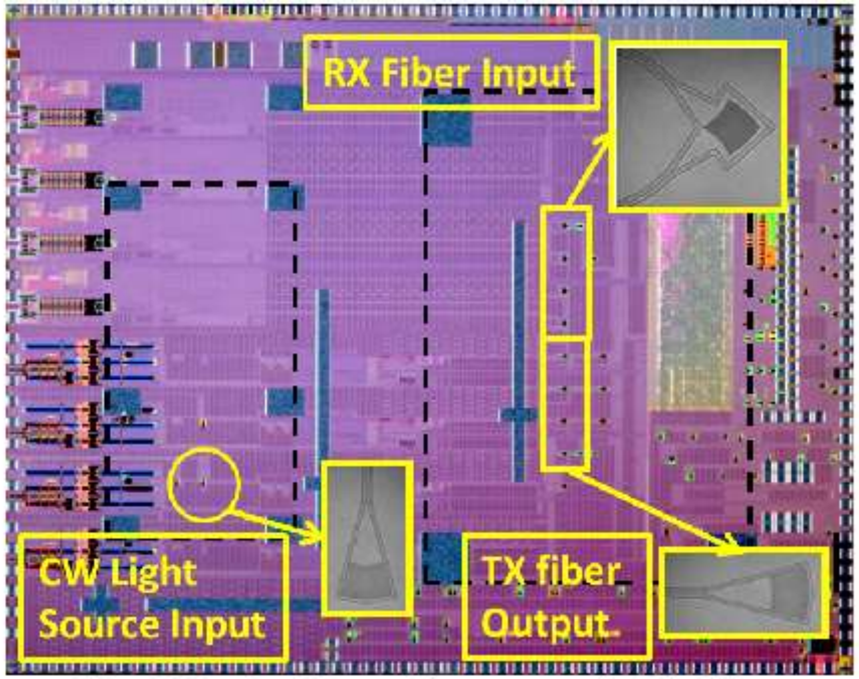


Fig. 7 Optical Interfaces to a 4x14 Gbps transceiver Si Photonics IC.

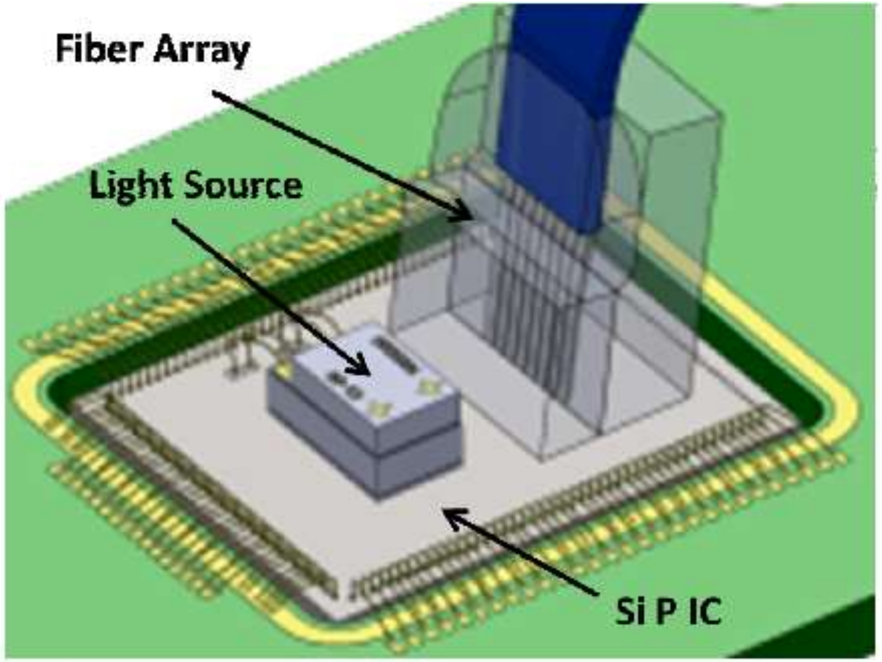
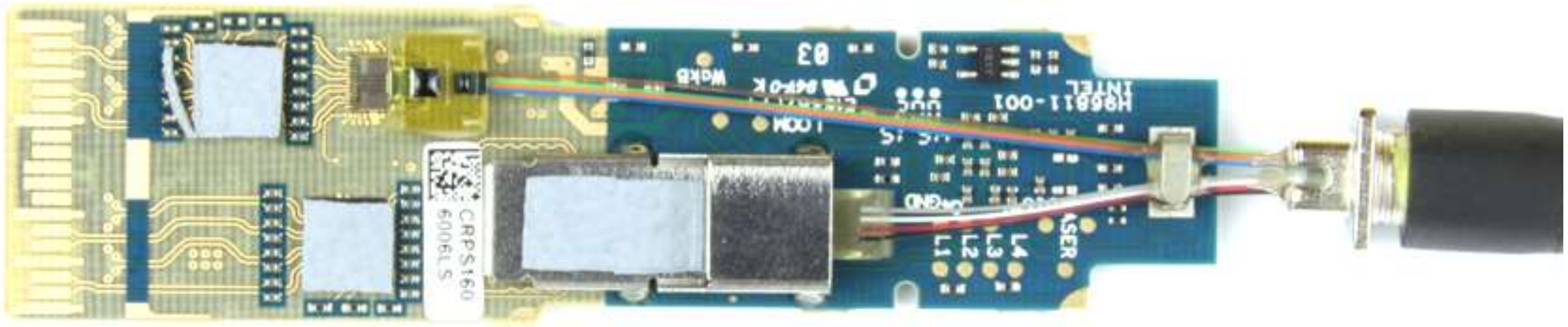
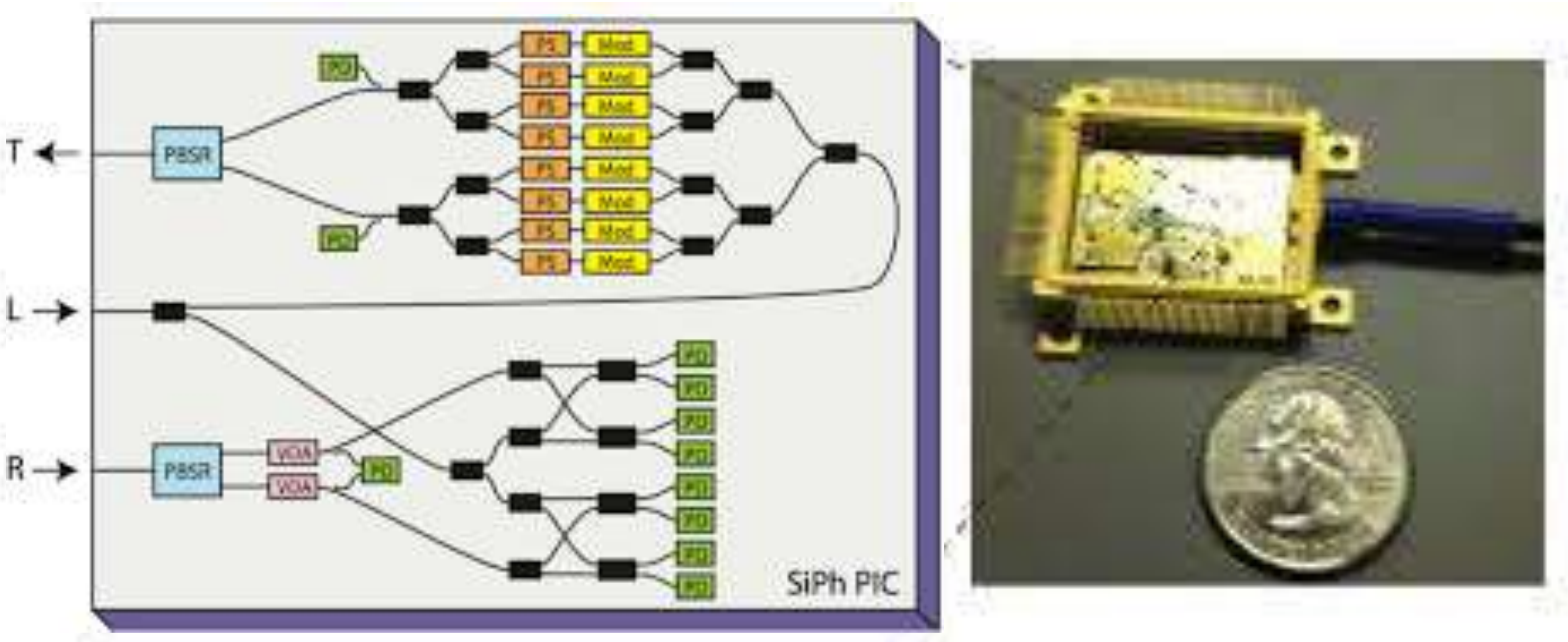


Fig. 8 Assembly of Si Photonic transceiver system: Si Photonics IC, light source and fiber interface.

Intel PSM4 SiPh QSFP28

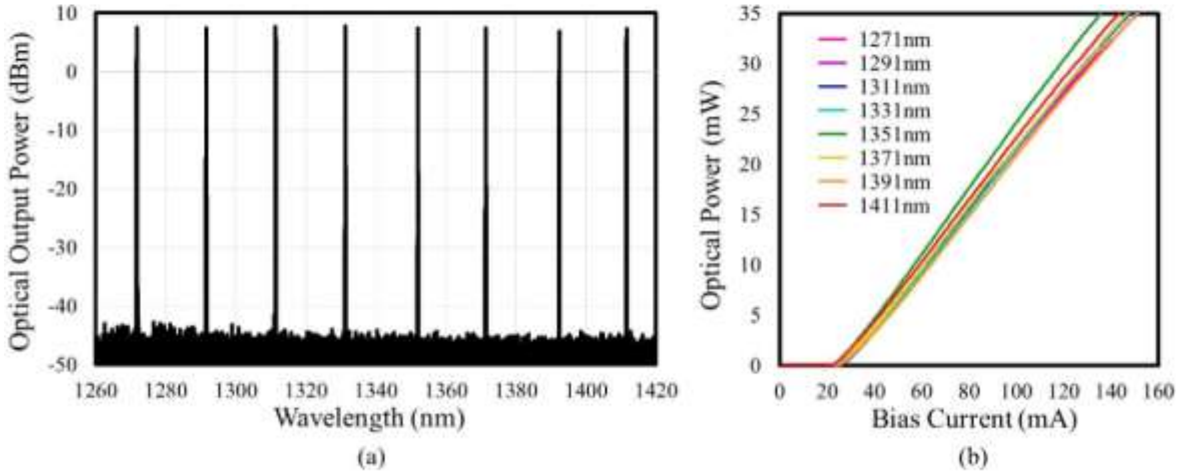


Acacia 100G Coherent SiPh



- The value proposition of SiPh is integration of many optical components
- To be successful, SiPh has to deliver performance not achievable with conventional optics, even if it costs more

Intel CWDM8 Prototype SiPh



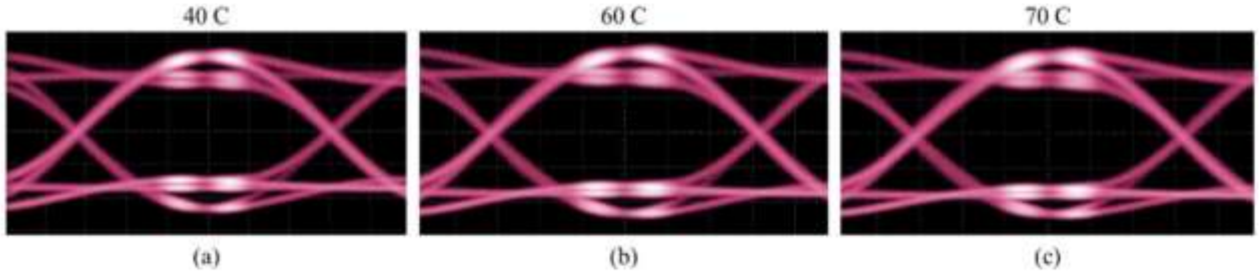


Figure 2: Representative output eye from a CWDM8 transmitter at (a) 40C, (b) 60C, and (c) 70C

Jeffrey B. Driscoll, et al., “First 400G 8-Channel CWDM Silicon Photonic Integrated Transmitter”, 2018 IEEE 15th International Conference on Group IV Photonics (GFP), 29-31 Aug. 2018.

Luxtera shipped an 8 channel PSM8 SiPh product)

SiPh Predictions

- SiPh 4 Channel transceivers have no advantage over conventional optics
- The stampede of 400G DR4 QSFP-DD SiPh transceivers from Intel, Cisco/Luxtera, Cisco/Acacia, Elenion, (Finisar before dropping out of the race), and other smaller companies will get no ROI on their investment
- Me too products rarely bring success
- SiPh has to deliver unmatched performance only achievable with large scale photonic integration.
- To be successful, SiPh has to be about value, not price.
- There is no other way to justify the huge investment required

Thank You