



LIGHTWAVE LOGIC™
Faster by Design

Photonic Integrated Circuits (PICs): Enabling our future...

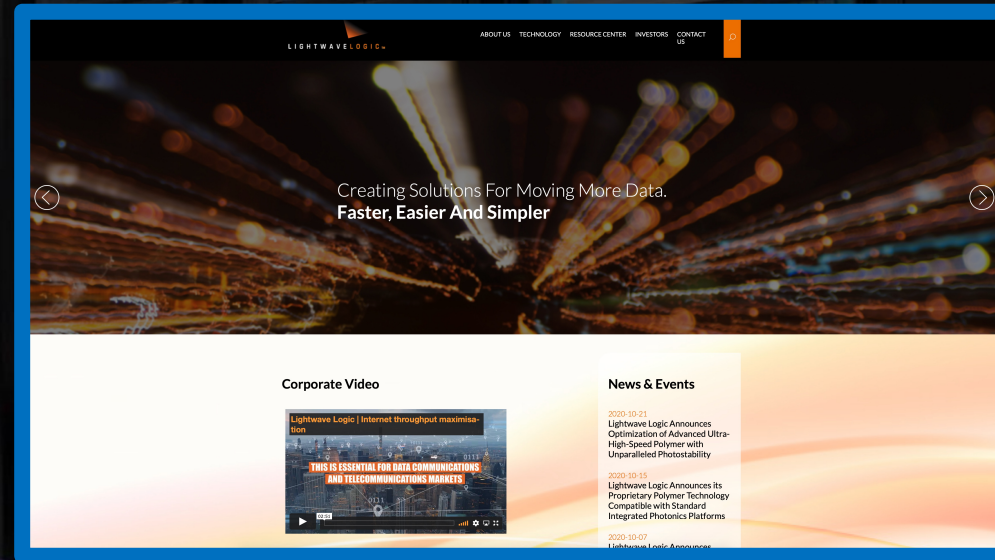
Michael Lebby
2nd June 2021

Photonic Integration Technology Center: Keynote

The information in this presentation may contain forward-looking statements within the meaning of the Private Securities Litigation Reform Act of 1995. You can identify these statements by use of the words "may," "will," "should," "plans," "explores," "expects," "anticipates," "continue," "estimate," "project," "intend," and similar expressions. Forward-looking statements involve risks and uncertainties that could cause actual results to differ materially from those projected or anticipated. These risks and uncertainties include, but are not limited to, general economic and business conditions, effects of continued geopolitical unrest and regional conflicts, competition, changes in technology and methods of marketing, delays in completing various engineering and manufacturing programs, changes in customer order patterns, changes in product mix, continued success in technological advances and delivering technological innovations, shortages in components, production delays due to performance quality issues with outsourced components, and various other factors beyond the Company's control.

This orange bar is the takeaway summary from each slide...

Slides will be posted at our website: www.lightwavelogic.com



Sit back...relax (no need to take notes!)

- ❑ The environment
- ❑ Markets
- ❑ Technologies
 - ❑ Cost/performance, data rates & speed, packaging
- ❑ Roadmaps
- ❑ Summary

3 questions to remember today...

- Will PIC photonics **enable** many things and will it be part of our lifestyle?
- Will photonics will be **integrated** – just like ICs 50 years ago and become the engine for new designs?
- Will integrated photonics (PICs) **enable** new products?

What might be the impact of PICs over the next decade?



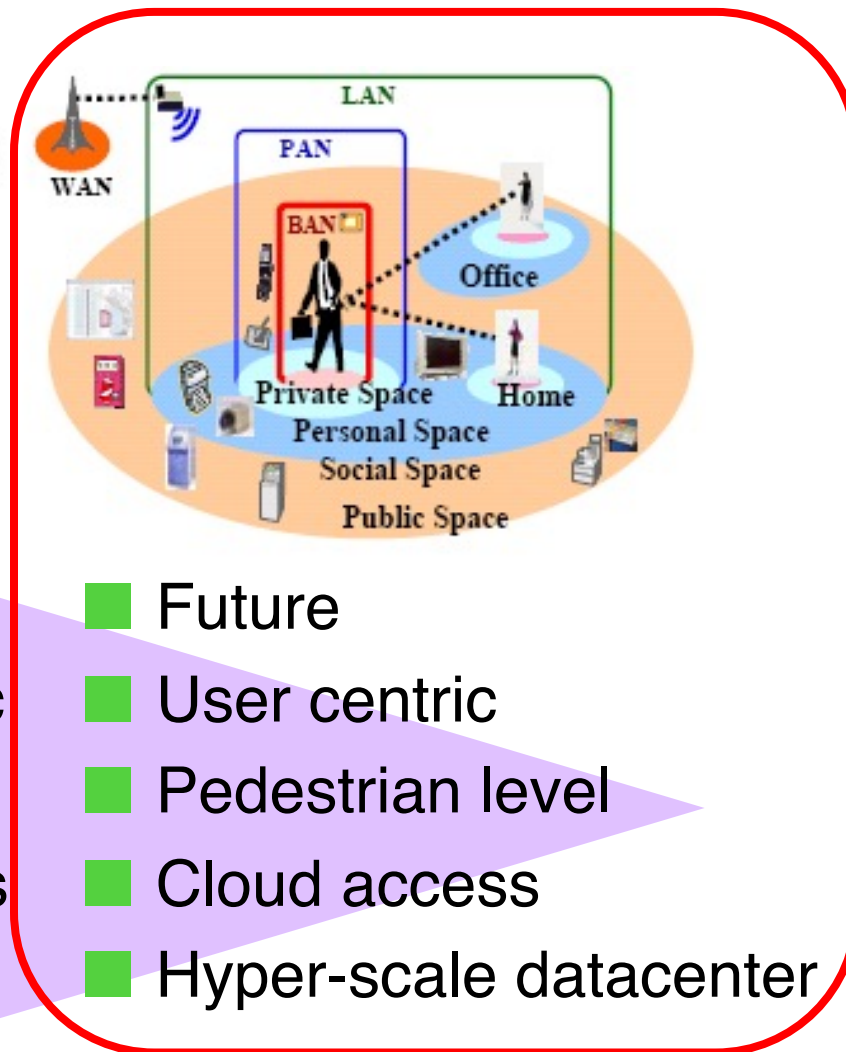
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The environment: quick review



The internet as a catalyst for change in lifestyle...



■ Before

■ Computer centric

■ Experts level

■ Data exchange

■ Exchange

■ Today

■ Network centric

■ Trained level

■ Archival access

■ Datacenter

■ Future

■ User centric

■ Pedestrian level

■ Cloud access

■ Hyper-scale datacenter

Use of heavy data...

Lifestyle evolves towards personal space...

What is affecting our lifestyle change?

- Virtual lifestyle – working from home
- Use of lots of data...
- Video
- New applications (AR/VR)...

Data-centric applications

Cloud services

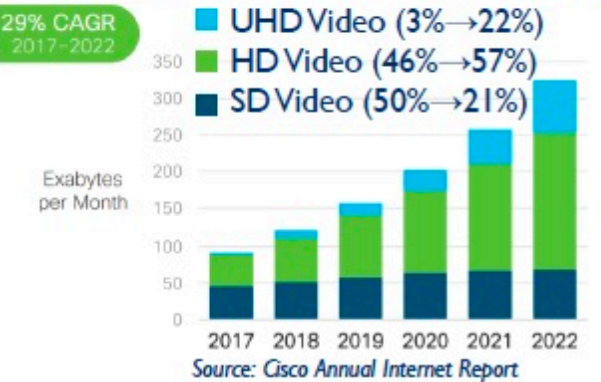
Industrial automation traffic

Video streaming at higher-definition (4k or 8k)

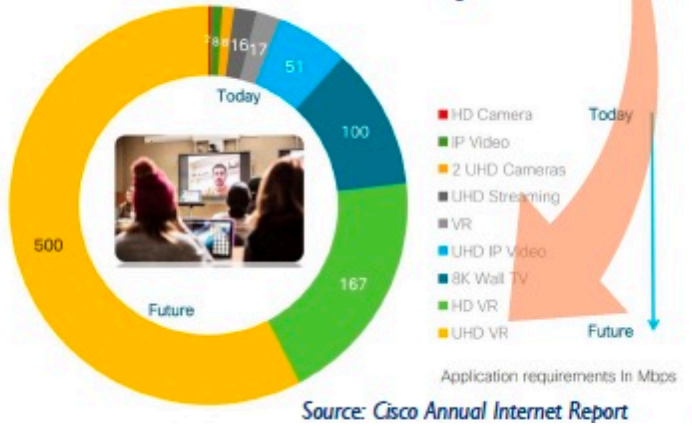
Emerging applications



Global internet video traffic



Video data rates of today and the future

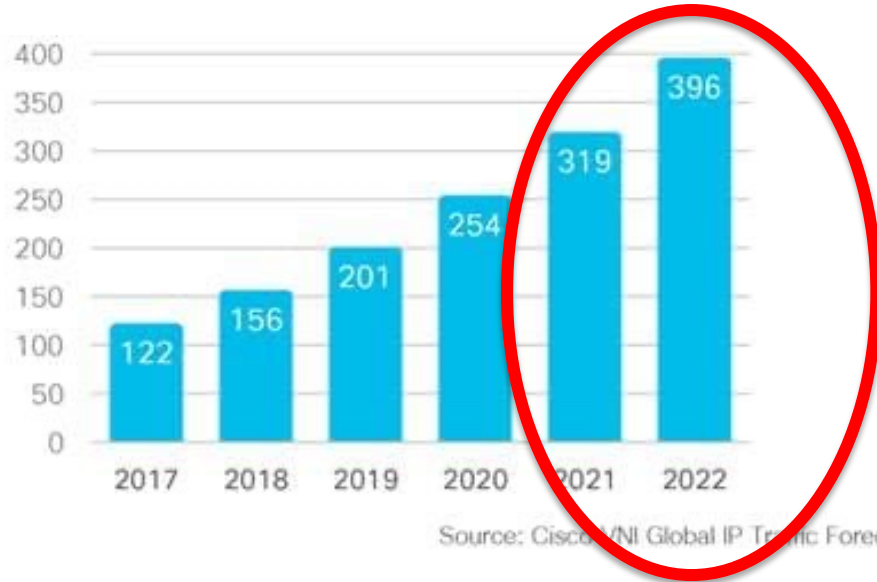


Video – use of heavy data...

Video driving internet traffic...

26% CAGR
2017-2022

Exabytes
per Month



Source: Cisco VNI Global IP Traffic Forecast, 2017-2022

~400 Exabytes per month
or
~4 Yottabytes per year today

- Old phone Kbps →
- Home Mbps →
- Business Gbps →
- Datacenter Tbps →
- Hyperscale DC →
- Traffic last few yrs →
- Traffic today →
- Traffic tomorrow →

International
Metric

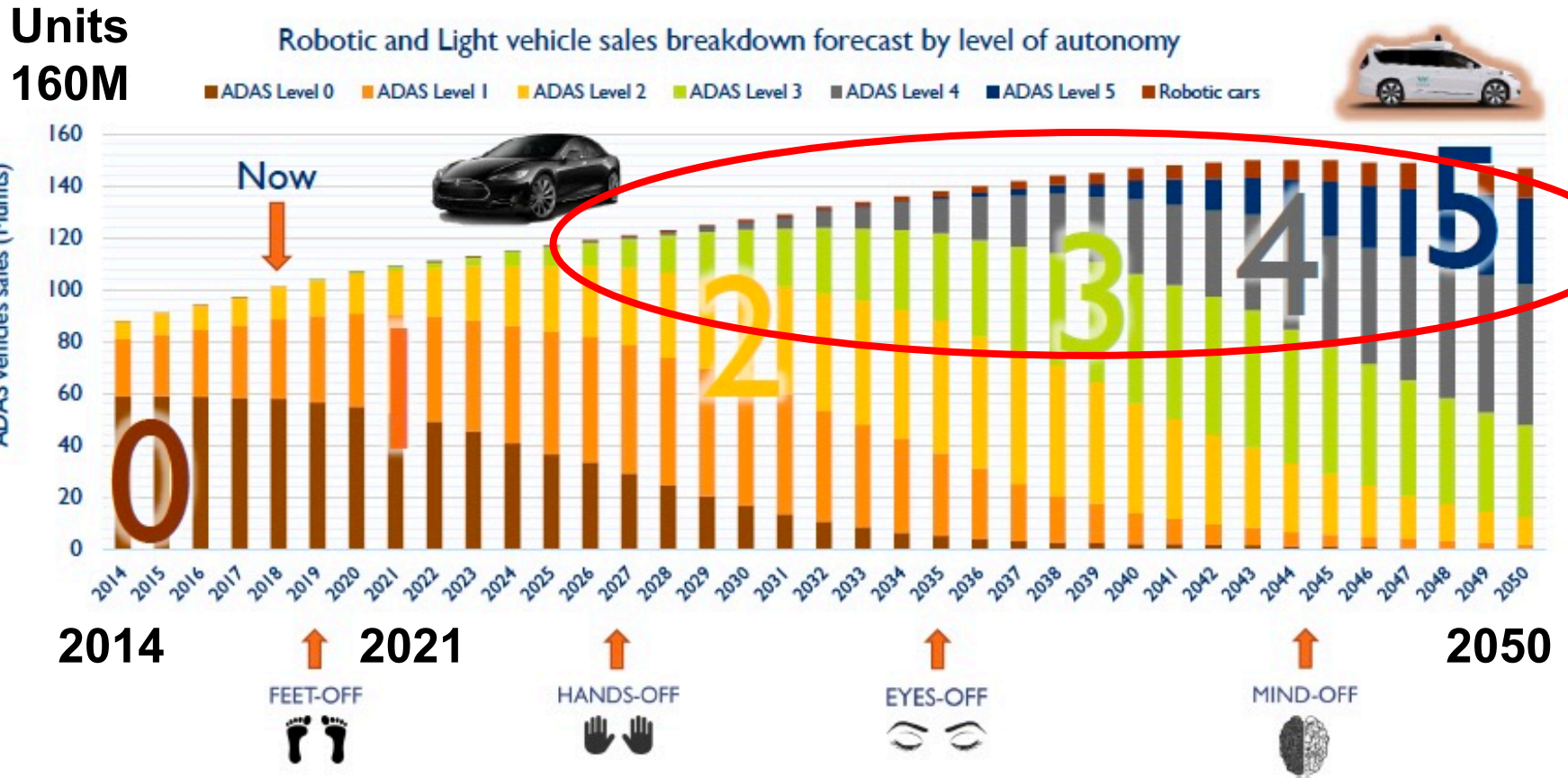
- Kilo = 10^3
- Mega = 10^6
- Giga = 10^9
- Tera = 10^{12}
- Peta = 10^{15}
- Exa = 10^{18}
- Zetta = 10^{21}
- Yotta = 10^{24}

NB: SI prefixes stop at Yotta...

Virtual lifestyle is now the 'new normal'

New trends → Automotive

- Networking, LIDAR, sensing, cameras...
- Integrated systems will need PICs
- Level 4&5 need more data → fuels datacenters and traffic



PICs will benefit from the 'heavy data' use...

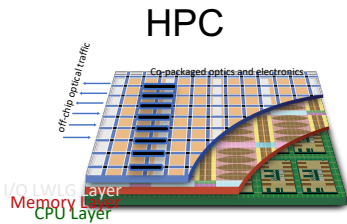
Markets

A server room with rows of black server racks. The scene is illuminated by vibrant, glowing light trails in shades of blue, orange, and purple that swirl and flow through the aisles, suggesting high-speed data transmission or network activity. The word "Markets" is centered in the upper half of the image in a white, sans-serif font.

New market opportunities are growing

- 5G systems
- RF over fiber
- Automotive (LIDAR)
- Optical sensing
- Bio-photonic sensing
- Medical
- Instrumentation
- Fiber comms
- HPC
- DCI

Datacenter

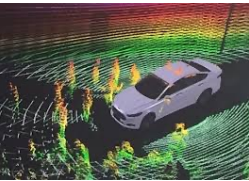


Source: Mitsubishi Electric, Luxtera, IBM, Google

5G



RF over fiber



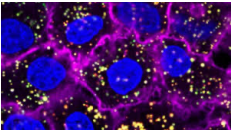
Automotive



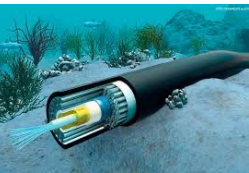
Medical



Bio sensing



Submarine FO

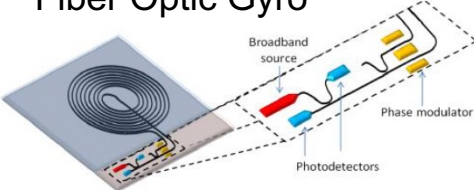


Immunoassays



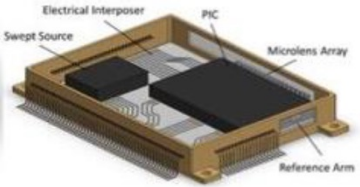
courtesy of Genalyte

Fiber Optic Gyro



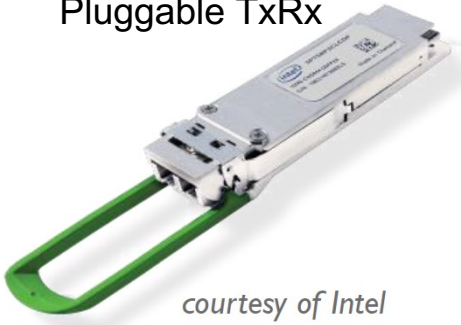
courtesy of Optics Express

OCT



courtesy of OCTCHIP

Pluggable TxRx



courtesy of Intel

LiDAR



courtesy of SiLC

Broad applications for PIC platforms...that send/receive optical data...

Photonics expected to grow significantly

2030 photonics
(rough forecasts*)

- 5G systems ~\$4-10B
- RF over fiber ~\$2-5B
- Automotive (LIDAR) ~\$20-30B
- Optical sensing ~\$2-5B
- Bio-photonic sensing ~\$2-5B
- Medical ~\$5-10B
- Instrumentation ~\$1-3B
- Fiber comms ~\$40-60B
- HPC ~\$10-20B
- DCI ~\$20-30B

*Many market forecasts predict huge photonics opportunities

Automotive

RF over fiber

Bio sensing

5G

Pluggable TxRx

Datacenter

Medical

Fiber Optic Gyro

Submarine FO

Immunoassays

OCT

HPC

LiDAR

courtesy of Optics Express

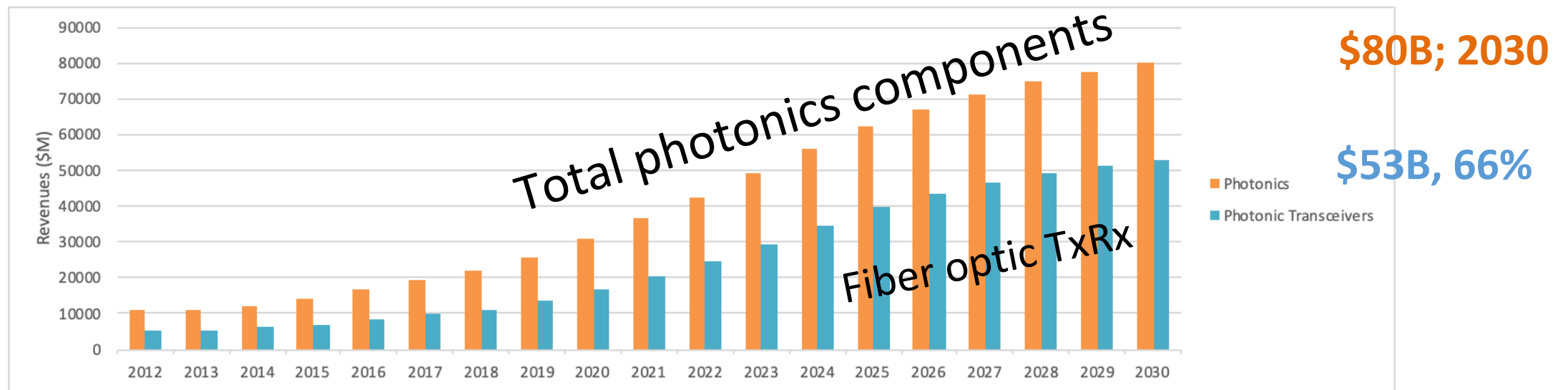
courtesy of OCTCHIP

courtesy of Genalyte

courtesy of SiLC

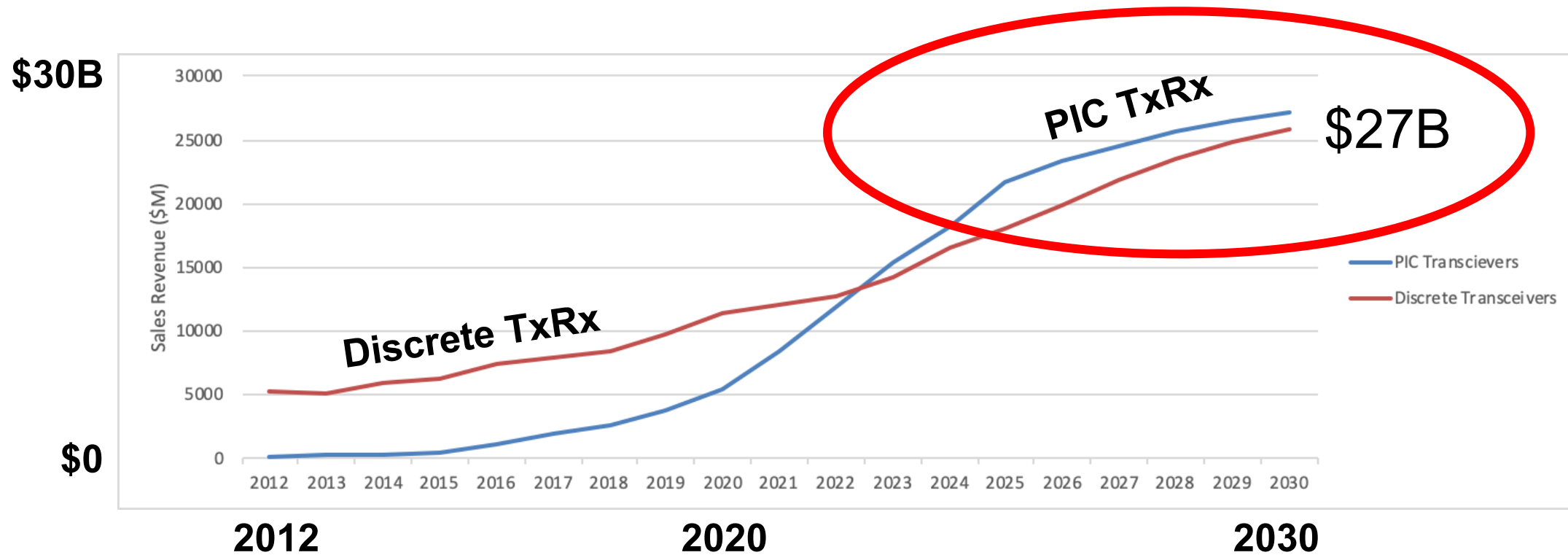
Markets for photonics are huge...

Fiber Optic transceivers are the perfect vehicle for PICs



Fiber optic transceiver explodes over the next decade...

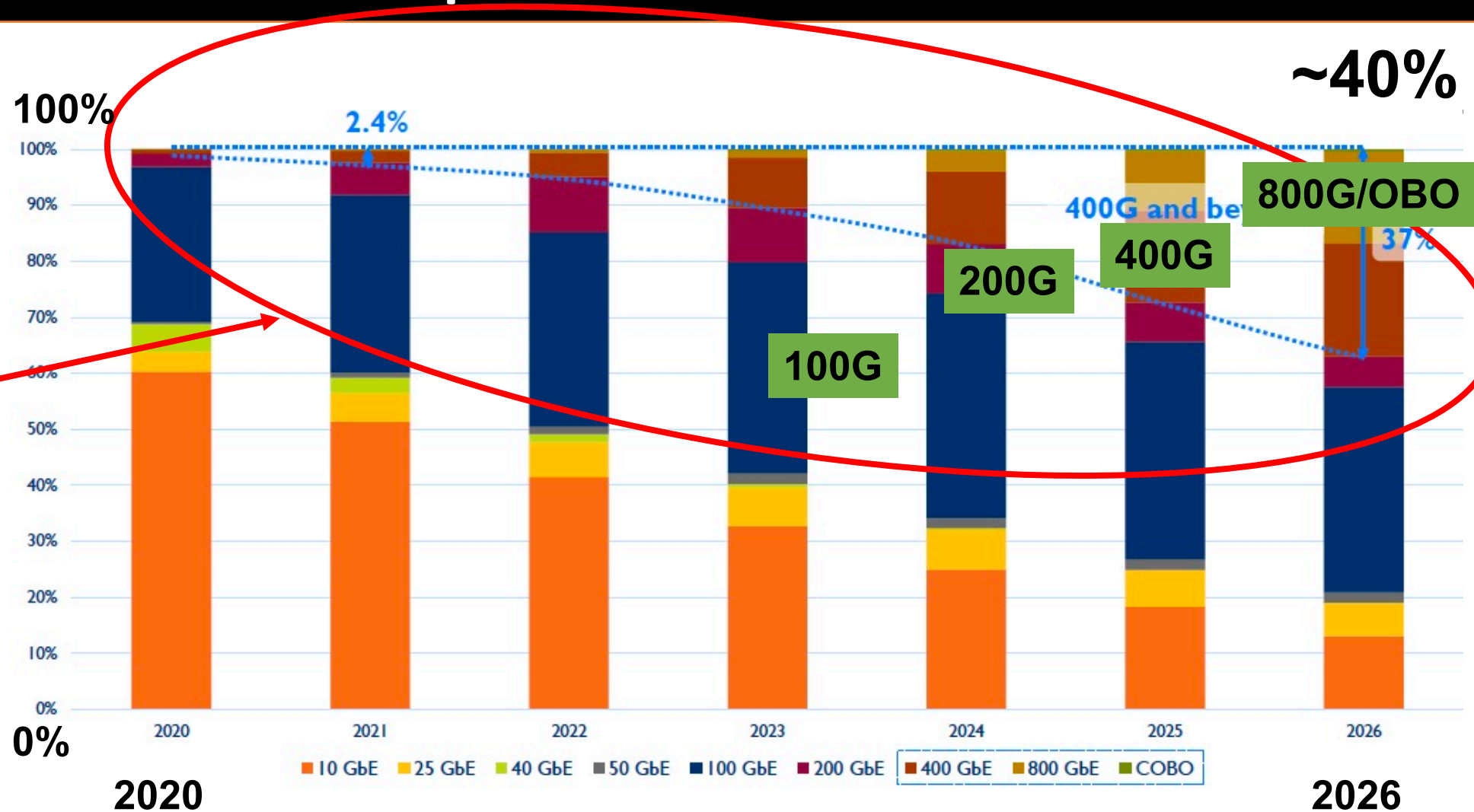
- PIC based transceivers lead the segment by 2030



PICs are expected to accelerate in their adoption over the decade...

Datacenter optical TxRx module penetration

- Strong growth of 400G, 800G and OBO (onboard optics)
- This represents a huge opportunity for PICs



PICs will be the engine for growth with 400, 800Gbps data rates...



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Technologies



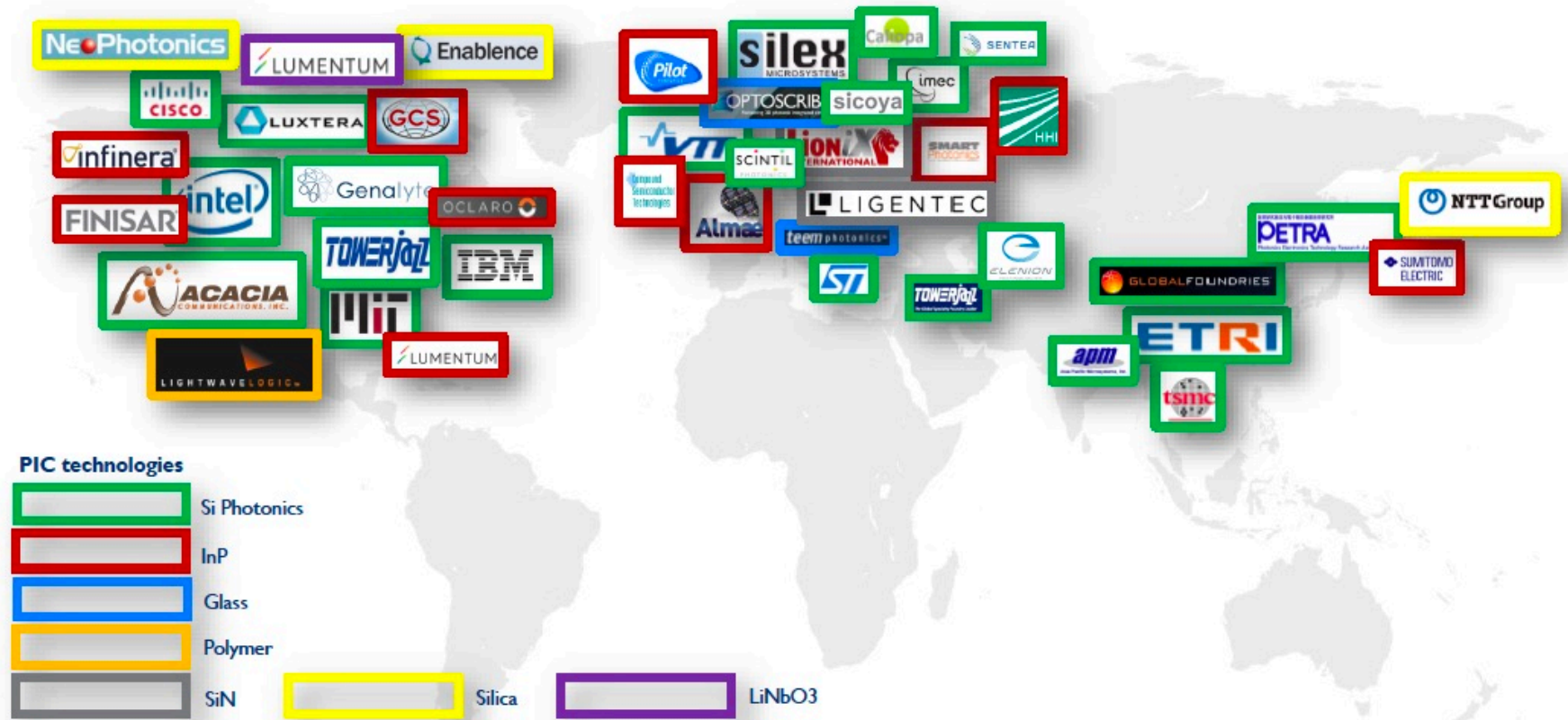
- Historic incumbent:
 - InP (Indium Phosphide)
 - GaAs (Gallium Arsenide)
- New incumbent:
 - SiP (Silicon photonics)

- ***New platforms and hybrid accelerators for PICs***
 - *Polymer, dielectrics, glass, lithium niobate thin film, plasmonic, barium titanate, silica, glass, germanium etc.*

Silicon photonics is the new kid on the block; new platforms → hybrid PICs

Sample global players and their PIC platforms

- Growth of Silicon photonics
- Trend towards hybrid platforms for PICs
- What combinations of technology make sense for hybrid PICs?



Challenge is to further PIC performance with other materials → hybrid PICs

Industry has 2 incumbent PICs...

Incumbent

Incumbent

Indium Phosphide

Silicon Photonics

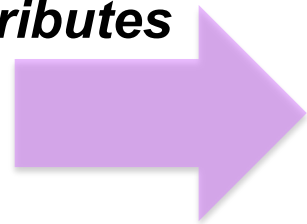
All InP

All SiPh

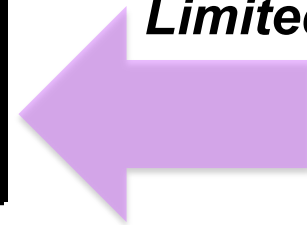
- InP laser ✓
- InP passives ✓
- InP modulator ✓ (limited)
- InP electronics ✓ (limited)

- Si laser ☒
- SiPh passives ✓
- Si modulator (limited)
- Si electronics ✓

Limited attributes



Limited attributes



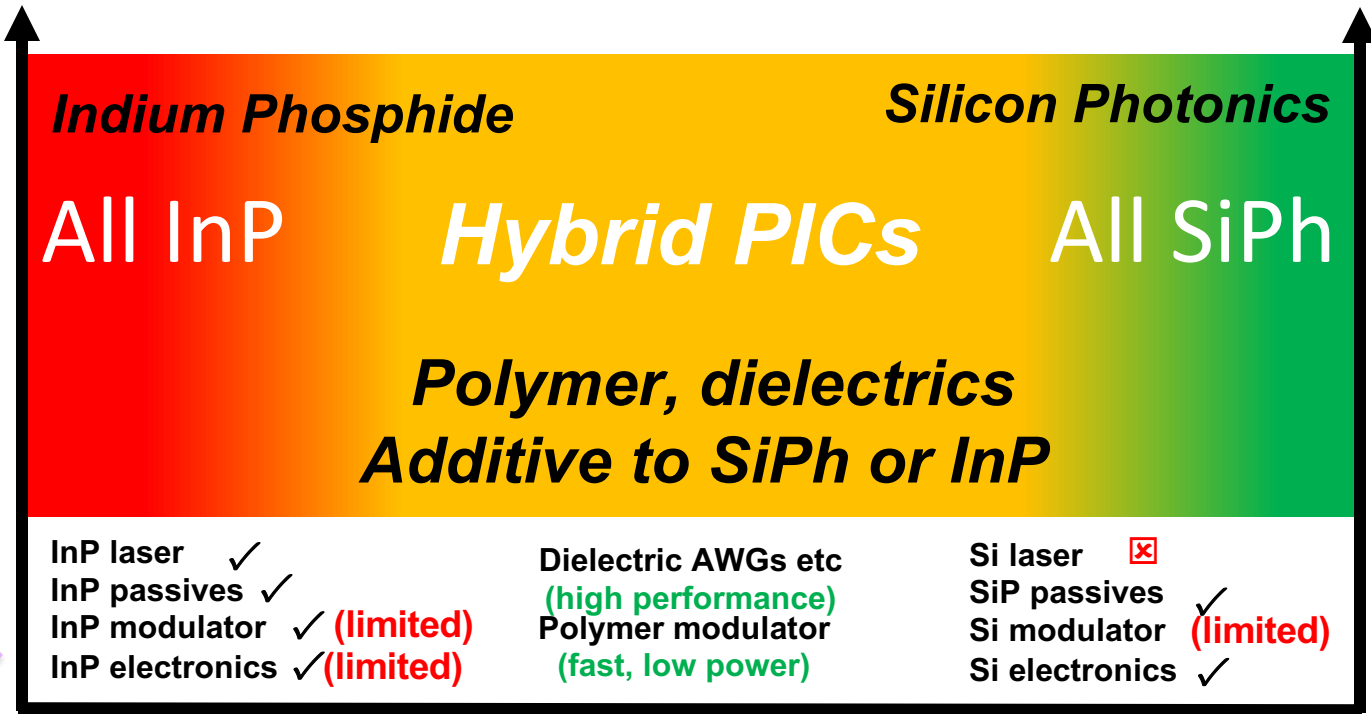
Incumbent technologies can't do everything...need help from hybrid PIC technologies...

Hybrid PICs increase performance...

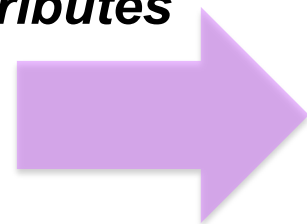
New hybrid PICs

Incumbent

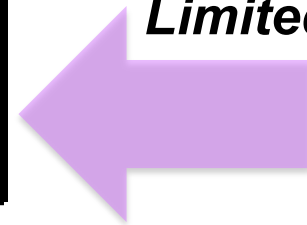
Incumbent



Limited attributes



Limited attributes



Hybrid PICs can boost performance of PICs



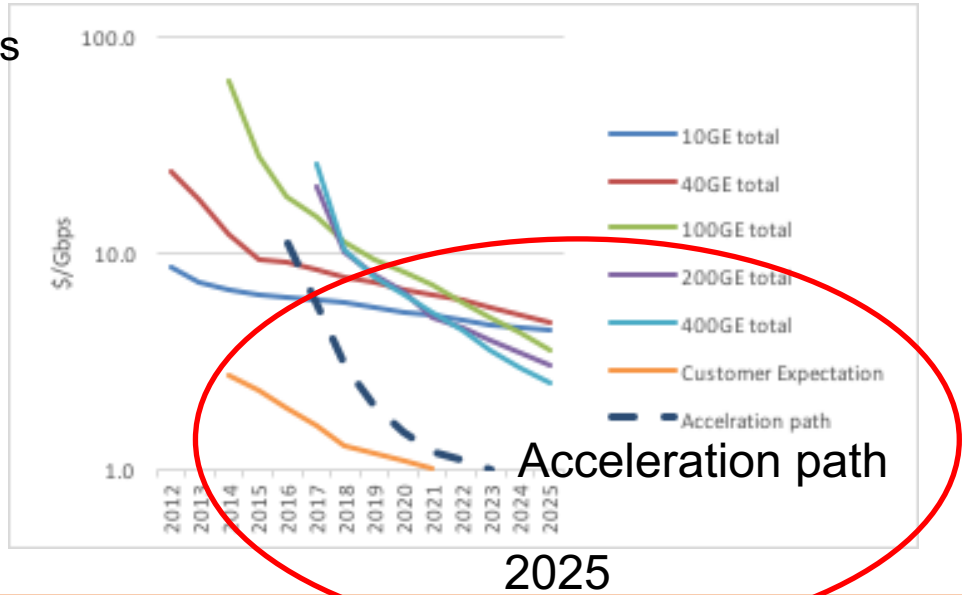
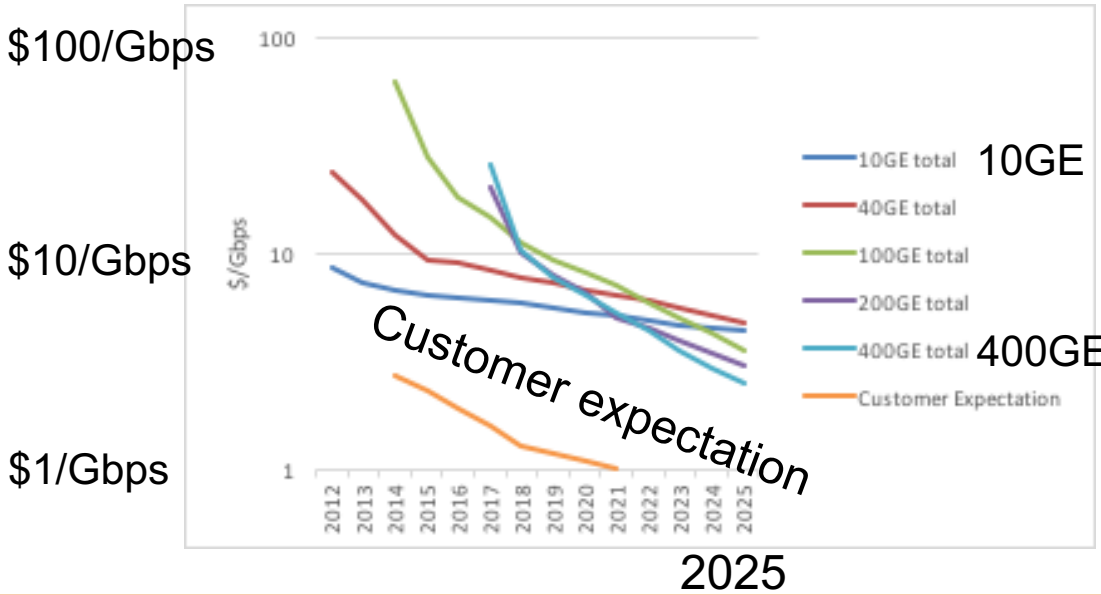
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Cost performance:
Achieving $< \$1/\text{Gbps}$ will open
new markets for PICS...

Motivators for PICs in fiber optics

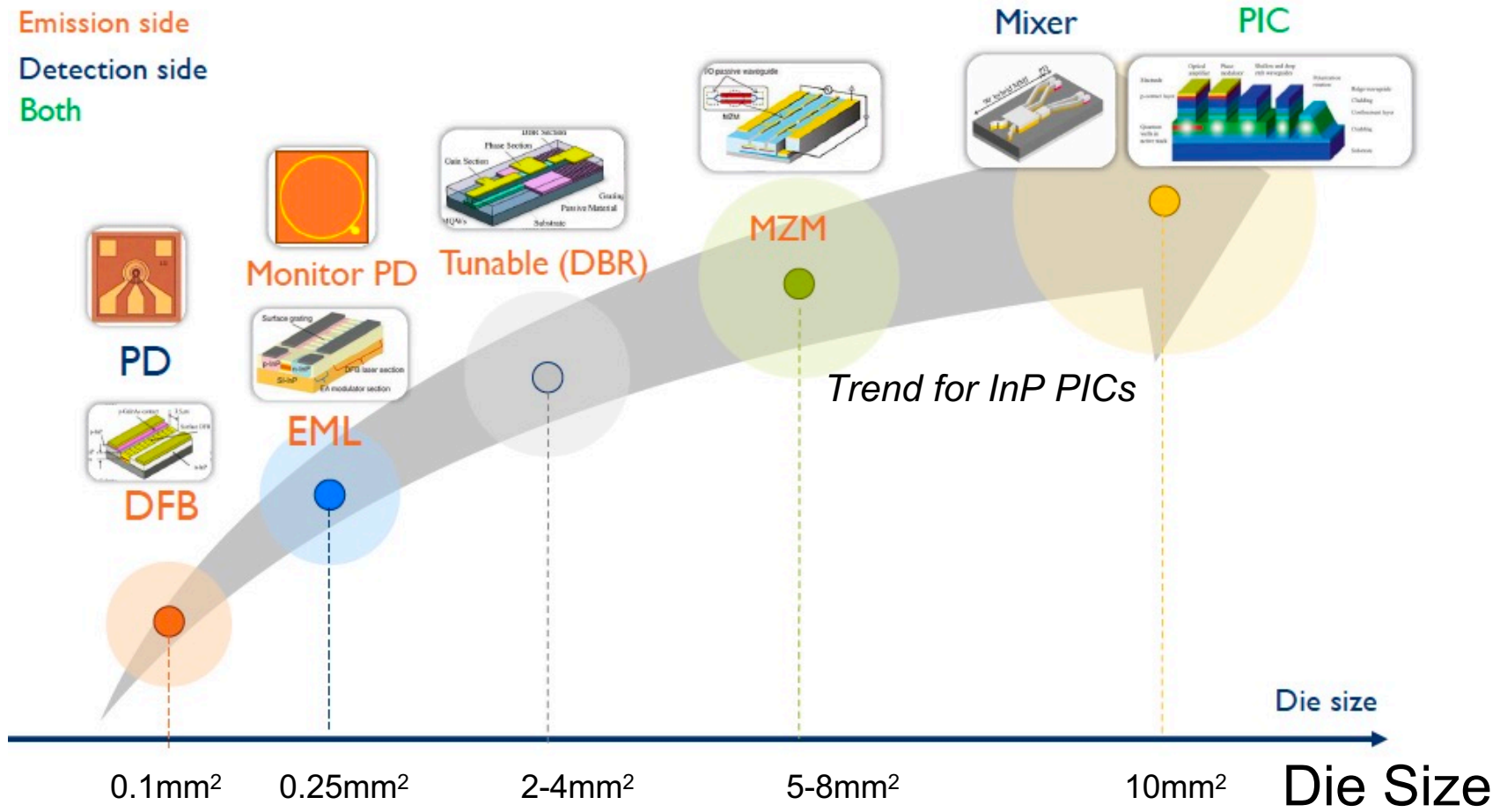
- Industry is expected to lag the wishes of customers at datacenters
 - Challenge: \$0.5/Gbps for 800G link is \$400 (or \$200 each end)



PICs can close this gap...

Increasing die size trends for PICs

- Complexity → bigger PIC chips
- Pressure to increase wafer size for economics of scale
- Hybrid PICs will allow both InP and SiPh to create competitive PICs in the next decade...



Industry can achieve cost/speed metrics through PIC platforms

Silicon foundries are hungry for 'opto' business

- CMOS fabrication plants want silicon photonics...new upside
- PDKs will drive the hybrid integration of PIC platforms



*PDK = Process Development Kit

Drive to 200/300mm allows competitive PIC cost/volume



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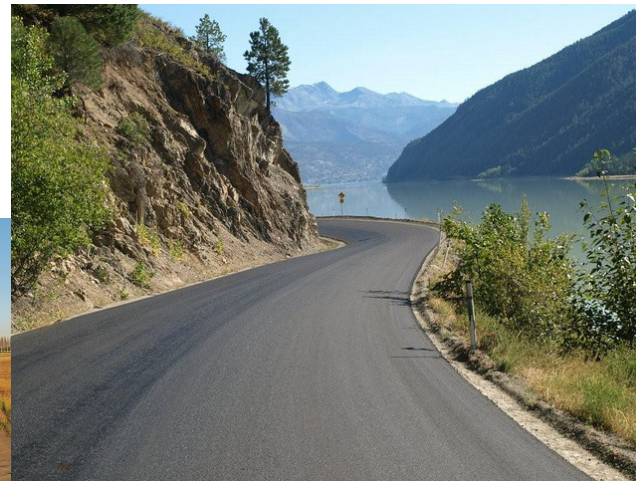
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PIC speed:
Can we make PIC
devices faster?



Traffic capacity: road analogy

Good roads: Faster cars:
more traffic capacity

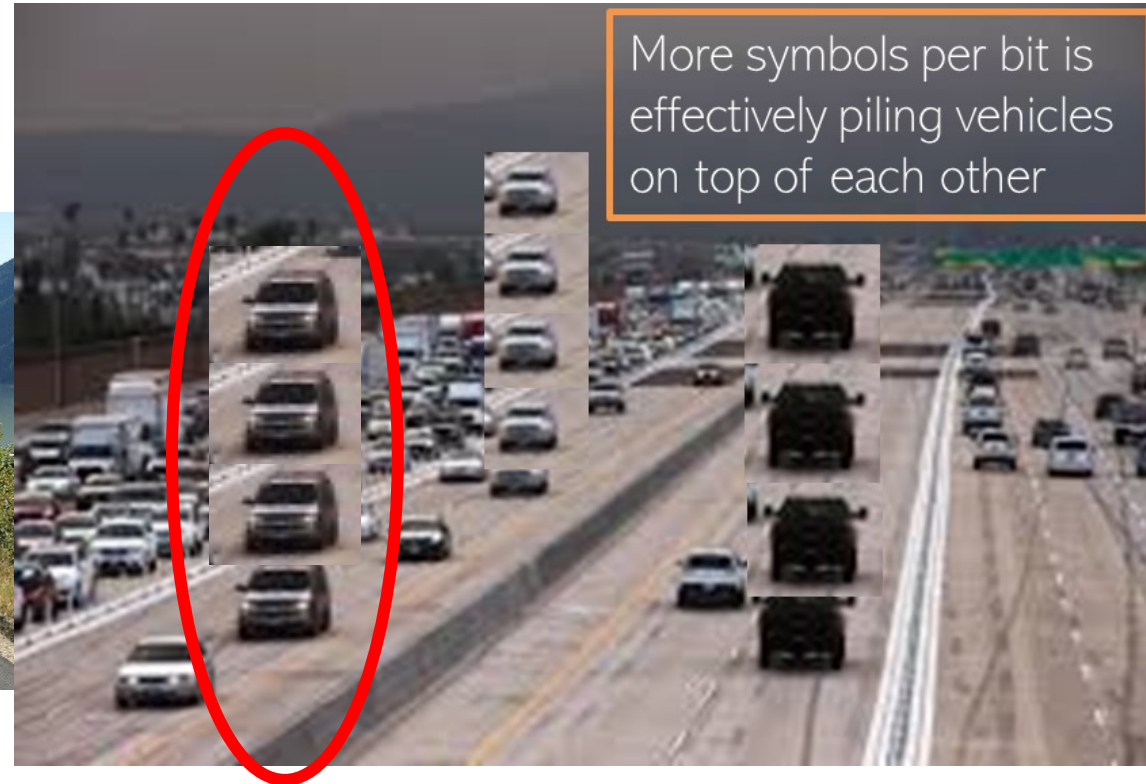


More lanes: more traffic capacity



We have already finished the easy things → like paving the road, adding more lanes...

Sending more data down the same lane (channel)...



Industry has already done the harder stuff like 'higher order modulation' [PAM4, QAM, etc.]

What about speed?

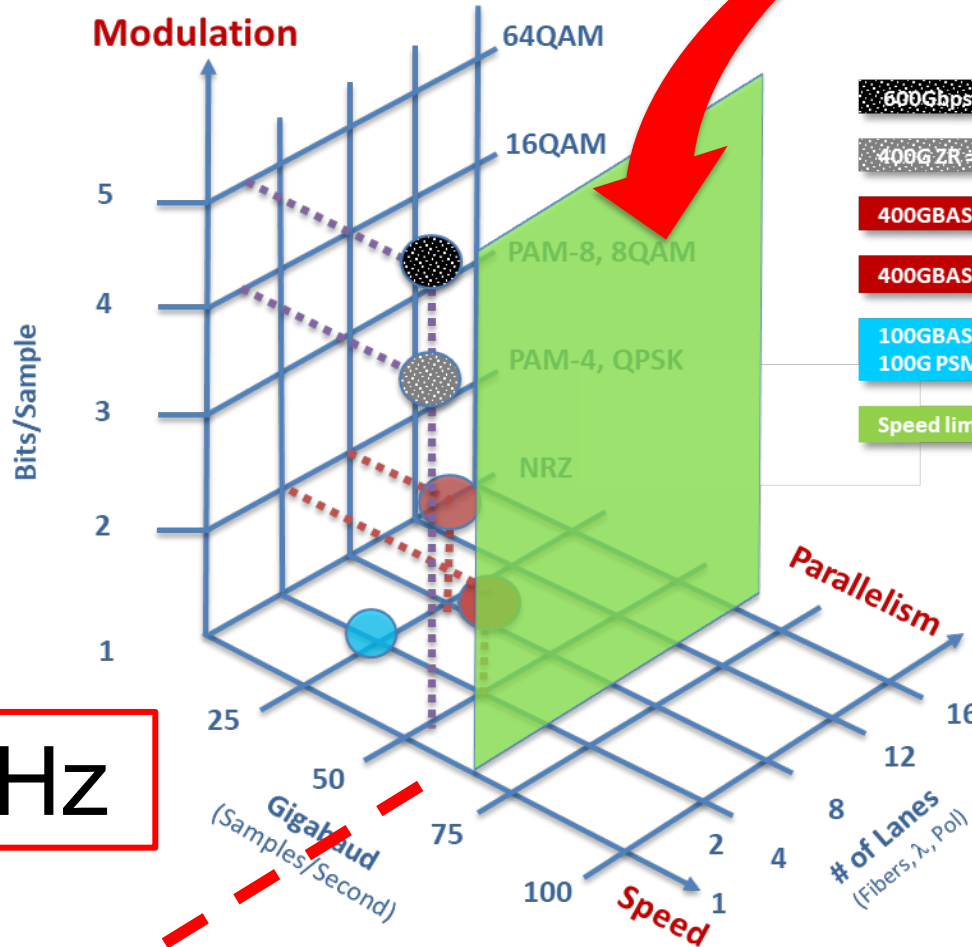


Still ~60 mph

10 mph → 60 mph

Speed has hit a plateau...

Speed limited by conventional photonics



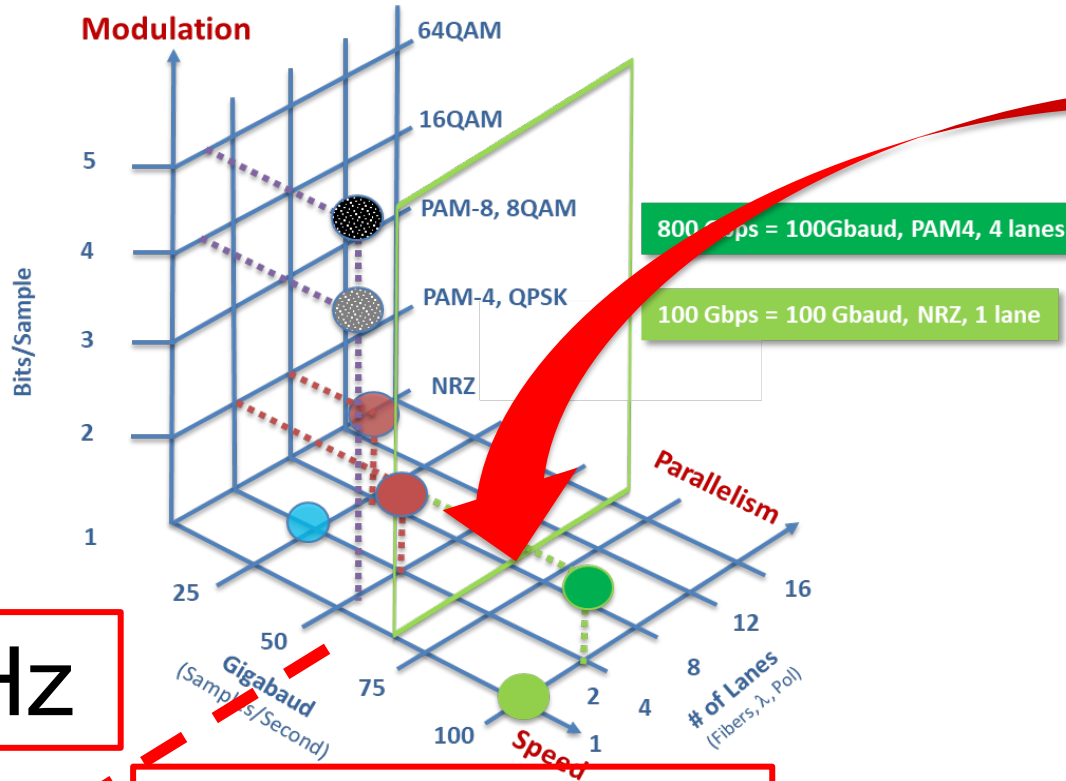
- 600Gbps = 64 Gbaud, 64QAM, 2 polarizations
- 400G ZR = 50Gbaud, 16QAM, 2 polarizations
- 400GBASE-DR4/ 400G FR4= 50 Gbaud, PAM4, 4 wavelengths
- 400GBASE-LR8= 25 Gbaud, PAM4, 8 wavelengths
- 100GBASE-LR4/100G CWDM4 = 25 Gbaud, NRZ, 4wavelengths
- 100G PSM4 = 25 Gbaud, NRZ, 4 fibers
- Speed limitation of optical devices

30-40GHz

3dB bandwidth; >35GHz is ~50Gbps NRZ or ~100GBaud PAM4

Speeds of optical devices limited to around 30-40GHz

One way to get to 800 and 1600Gbps: faster PICs (modulator helps) WAVELOGIC™



30-40GHz

~70GHz
→ faster PICs

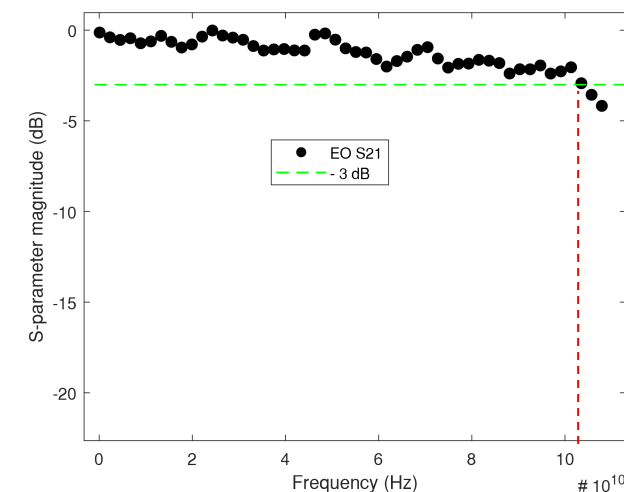
3dB bandwidth;
~70GHz is
~100Gbps NRZ or
~200GBaud PAM4
Double the speed

Can we make faster optical devices → PICs?

Polymers break the speed limit...over 100GHz



3dB Bandwidth >100GHz



Faster PICs → alleviates circuit complexity in networking systems



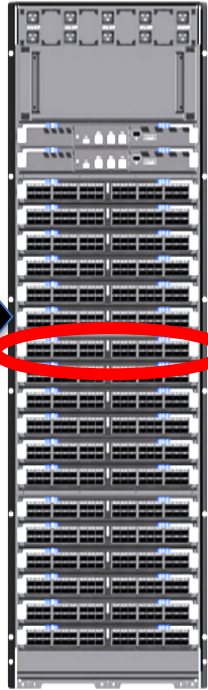
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Packaging:
Can we package PICs just
like IC electronics?

Inside a datacenter there are racks...

Faceplate



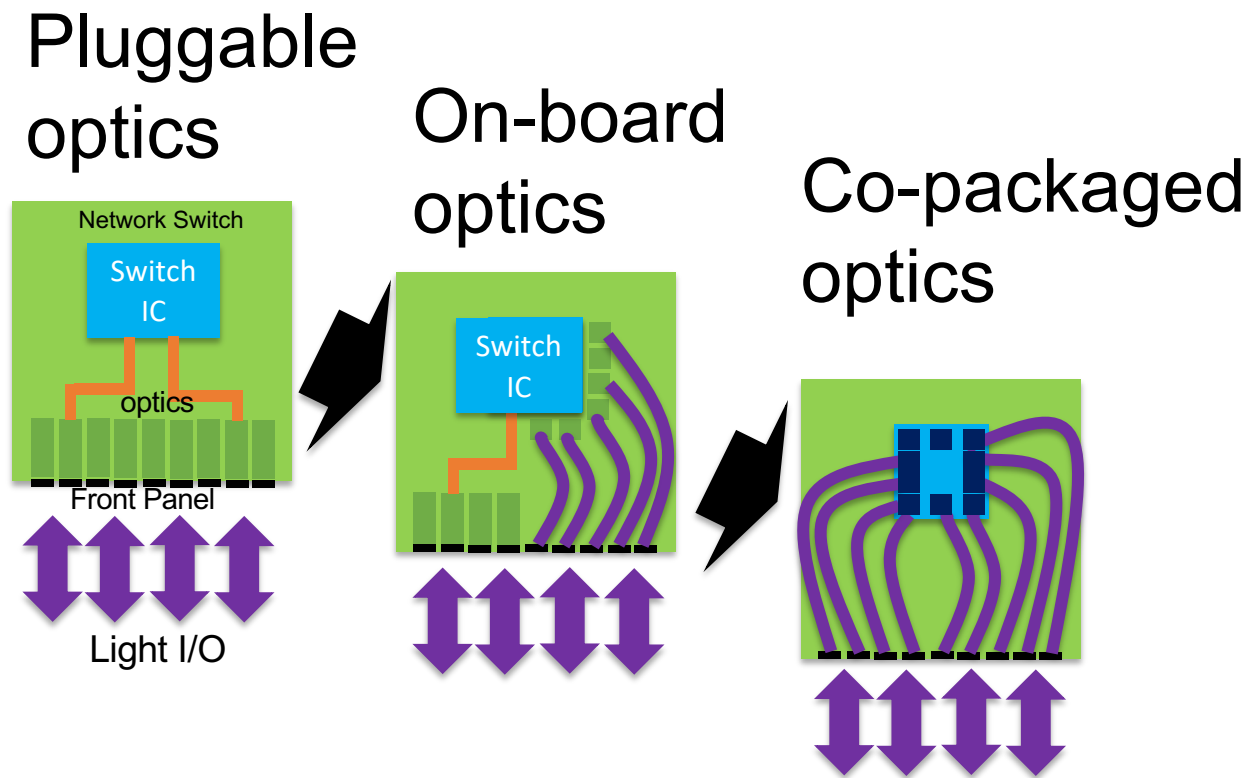
Equipment capacity is limited by how many transceivers can fit on the faceplate



Faceplates limit the flow of data → just like a blocked artery...

Re-think how to unblock the artery...

Pluggable transceivers are not scaling with data flow...



Co-packaging gets the optics right to the IC switch chip...

Photonics integration → electronics and photonics

Top View

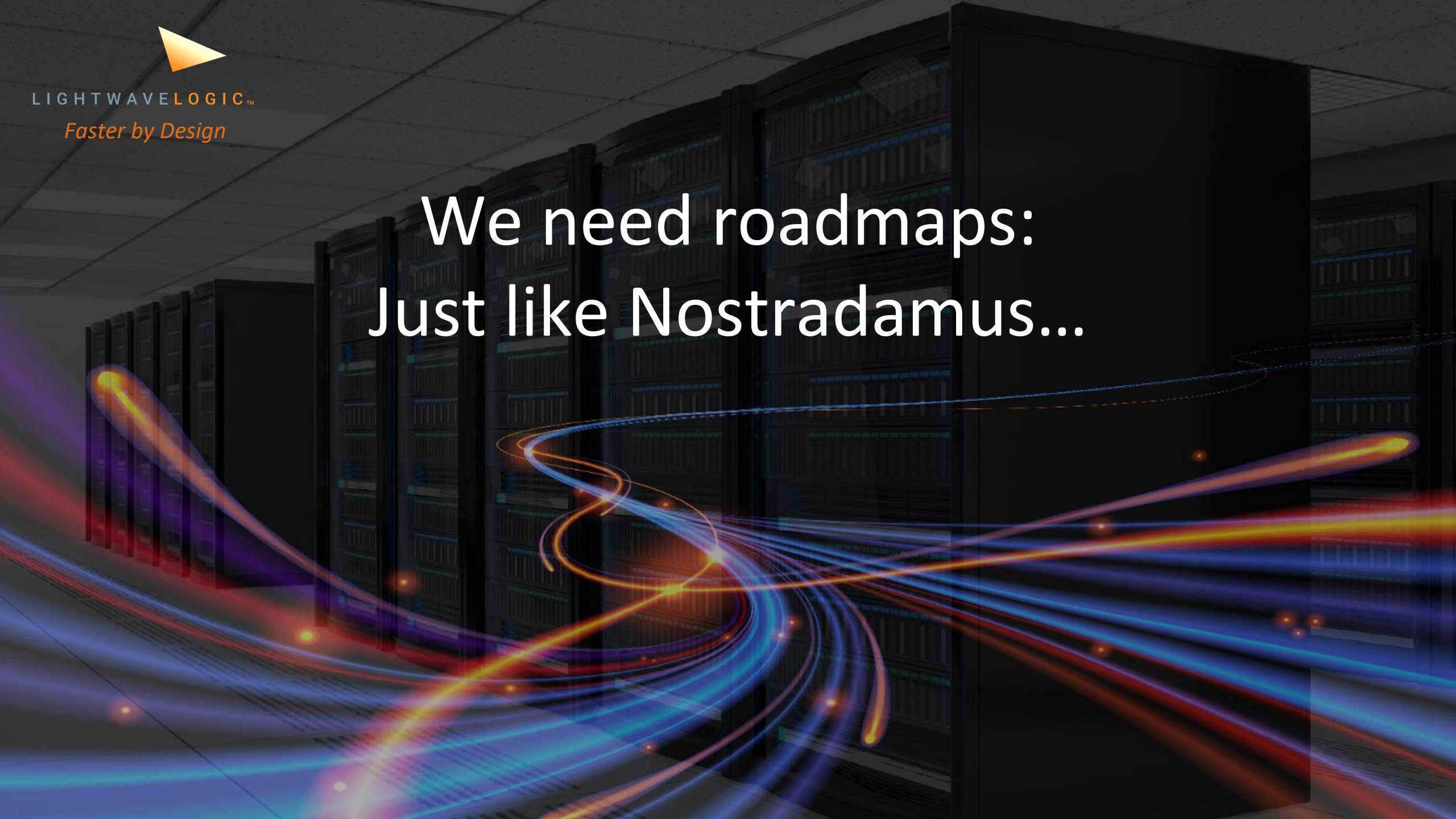
Co-packaging (and chip scale packaging) are now considered *inevitable*

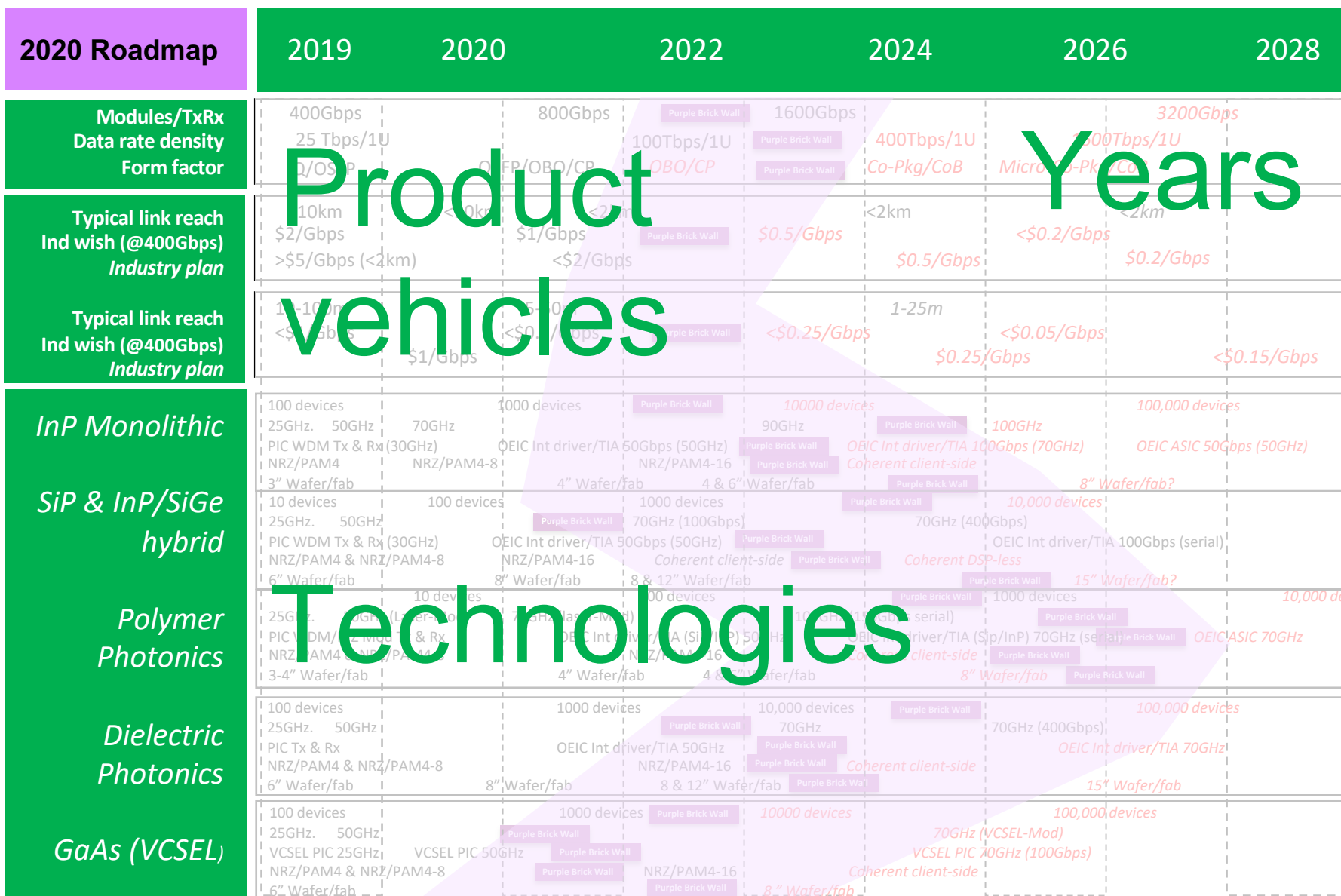


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We need roadmaps:
Just like Nostradamus...





Tough to design
>1600Gbps+
TxRx
modules...

Tough to design
>70GHz
bandwidth
devices...

Some
technologies
have higher
performance....

How to
scale PIC
integration?

Normal Black Font
= Reasonably expected based on current efforts

Purple Brick Wall
= Technology cost barrier

Slanted Red Font
= Major industry effort required for commercialization

Sources: LWLG, iNEMI, AIM Photonics, Photon Delta

Simple metrics

2020 Roadmap	2019	2020	2022	2024	2026	2028
Modules/TxRx Data rate density Form factor	400Gbps 25 Tbps/1U Q/OSFP	800Gbps OSFP/OBO/CP	100Tbps/1U OBO/CP	1600Gbps Co-Pkg/CoB	3200Gbps Micro-Co-Pkg/CoB	
Typical link reach Ind wish (@400Gbps) Industry plan	<10km \$2/Gbps >\$5/Gbps (<2km)	<10km \$1/Gbps <\$2/Gbps	<2km \$0.5/Gbps	<2km \$0.2/Gbps	<2km \$0.2/Gbps	
Typical link reach Ind wish (@400Gbps) Industry plan	10-100m <\$1/Gbps	5-50m <\$0.5/Gbps	1-25m <\$0.25/Gbps	1-25m \$0.25/Gbps	<2km <\$0.05/Gbps	<2km <\$0.15/Gbps
InP Monolithic	100 devices 20GHz, 10GHz PIC WDM Tx & Rx (30GHz) NRZ/PAM4 & NRZ/PAM4-8 3-Wafer/fab	1000 devices 70GHz OEIC Int driver/TIA 50Gbps (50GHz) NRZ/PAM4-16 4 & 6" Wafer/fab	10000 devices 90GHz OEIC Int driver/TIA 100Gbps (70GHz) Coherent client-side 4 & 6" Wafer/fab	10000 devices 100GHz OEIC Int driver/TIA 100Gbps (70GHz) Coherent client-side 8" Wafer/fab?	100,000 devices 100GHz OEIC ASIC 50Gbps (50GHz) OEIC Int driver/TIA 100Gbps (70GHz) Coherent client-side 8" Wafer/fab?	100,000 devices 100GHz OEIC ASIC 50Gbps (50GHz) OEIC Int driver/TIA 100Gbps (70GHz) Coherent client-side 15" Wafer/fab?
SiP & InP/SiGe hybrid	10 devices 25GHz, 50GHz PIC WDM Tx & Rx (30GHz) NRZ/PAM4 & NRZ/PAM4-8 6-Wafer/fab	100 devices 70GHz (50Gbps) OEIC Int driver/TIA 50Gbps (50GHz) NRZ/PAM4-16 8" Wafer/fab	1000 devices 70GHz (100Gbps) Coherent client-side 8 & 12" Wafer/fab	10000 devices 100GHz (150Gbps serial) OEIC Int driver/TIA (SiP/InP) 50GHz Coherent client-side 8" Wafer/fab	10000 devices 100GHz (150Gbps serial) OEIC Int driver/TIA (SiP/InP) 70GHz (400Gbps) Coherent client-side 8" Wafer/fab	10,000 devices 100GHz (150Gbps serial) OEIC Int driver/TIA 70GHz OEIC ASIC 70GHz 15" Wafer/fab
Polymer Photonics	25GHz, 50GHz PIC WDM/MZ Mod Tx & Rx NRZ/PAM4 & NRZ/PAM4-8 3-4" Wafer/fab	100 devices 70GHz (laser-Mod) OEIC Int driver/TIA 50Gbps (50GHz) NRZ/PAM4-16 4" Wafer/fab	1000 devices 70GHz OEIC Int driver/TIA 50Gbps (50GHz) NRZ/PAM4-16 4 & 6" Wafer/fab	10000 devices 100GHz (150Gbps serial) OEIC Int driver/TIA (SiP/InP) 70GHz (400Gbps) Coherent client-side 8" Wafer/fab	10000 devices 100GHz (150Gbps serial) OEIC Int driver/TIA (SiP/InP) 70GHz (400Gbps) Coherent client-side 8" Wafer/fab	100,000 devices 100GHz (150Gbps serial) OEIC Int driver/TIA 70GHz OEIC ASIC 70GHz 15" Wafer/fab
Dielectric Photonics	25GHz, 50GHz PIC Tx & Rx NRZ/PAM4 & NRZ/PAM4-8 6" Wafer/fab	100 devices 70GHz OEIC Int driver/TIA 50Gbps (50GHz) NRZ/PAM4-16 8" Wafer/fab	1000 devices 70GHz OEIC Int driver/TIA 50Gbps (50GHz) NRZ/PAM4-16 8 & 12" Wafer/fab	10000 devices 100GHz OEIC Int driver/TIA 50Gbps (50GHz) NRZ/PAM4-16 8 & 12" Wafer/fab	10000 devices 100GHz OEIC Int driver/TIA 50Gbps (50GHz) NRZ/PAM4-16 8 & 12" Wafer/fab	100,000 devices 100GHz OEIC Int driver/TIA 70GHz OEIC ASIC 70GHz 15" Wafer/fab
GaAs (VCSEL)	100 devices 25GHz, 50GHz VCSEL PIC 25GHz NRZ/PAM4 & NRZ/PAM4-8 1.5" Wafer/fab	1000 devices 50GHz VCSEL PIC 50GHz NRZ/PAM4-16 8" Wafer/fab	10000 devices 70GHz VCSEL PIC 70GHz (100Gbps) NRZ/PAM4-16 8" Wafer/fab	10000 devices 70GHz VCSEL PIC 70GHz (100Gbps) NRZ/PAM4-16 8" Wafer/fab	10000 devices 70GHz VCSEL PIC 70GHz (100Gbps) NRZ/PAM4-16 8" Wafer/fab	100,000 devices 70GHz VCSEL PIC 70GHz (100Gbps) NRZ/PAM4-16 8" Wafer/fab

Normal R&D funding

Major investment in R&D to achieve goals

Tough to design >1600Gbps+ TxRx modules...

Tough to design >70GHz bandwidth devices...

Some technologies have higher performance....

How to scale PIC integration?

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Red means major industry efforts needed for commercialization

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Typical link reach Ind wish (@400Gbps) Industry plan	10-100m <\$1/Gbps	5-50m <\$0.5/Gbps \$1/Gbps	1-25m \$0.25/Gbps \$0.25/Gbps	1-25m \$0.25/Gbps \$0.25/Gbps	1-25m <\$0.05/Gbps \$0.25/Gbps	<\$0.15/Gbps
InP Monolithic	100 devices 25GHz, 50GHz PIC WDM Tx & Rx (30GHz) NRZ/PAM4 3" Wafer/fab	1000 devices 70GHz OEIC Int driver/TIA 50Gbps (50GHz) NRZ/PAM4-8 4" Wafer/fab	10000 devices 90GHz OEIC Int driver/TIA 100Gbps (70GHz) NRZ/PAM4-16 4" & 6" Wafer/fab	10000 devices 100GHz OEIC Int driver/TIA 100Gbps (70GHz) NRZ/PAM4-16 4" & 6" Wafer/fab	100,000 devices 100GHz OEIC ASIC 50Gbps (50GHz) NRZ/PAM4-16 8" Wafer/fab?	100,000 devices 100GHz OEIC ASIC 50Gbps (50GHz) NRZ/PAM4-16 8" Wafer/fab?
SiP & InP/SiGe hybrid	10 devices 25GHz, 50GHz PIC WDM Tx & Rx (30GHz) NRZ/PAM4 & NRZ/PAM4-8 6" Wafer/fab	100 devices 70GHz (100Gbps) OEIC Int driver/TIA 50Gbps (50GHz) NRZ/PAM4-16 8" Wafer/fab	1000 devices 70GHz (400Gbps) OEIC Int driver/TIA 100Gbps (serial) NRZ/PAM4-16 8" Wafer/fab	10000 devices 70GHz (400Gbps) OEIC Int driver/TIA 100Gbps (serial) NRZ/PAM4-16 8" Wafer/fab	10000 devices 70GHz (400Gbps) OEIC Int driver/TIA 100Gbps (serial) NRZ/PAM4-16 15" Wafer/fab?	10000 devices 70GHz (400Gbps) OEIC Int driver/TIA 100Gbps (serial) NRZ/PAM4-16 15" Wafer/fab?
Polymer Photonics	10 devices 25GHz, 50GHz (Laser-Mod) PIC WDM/MZ Mod Tx & Rx NRZ/PAM4 & NRZ/PAM4-8 3-4" Wafer/fab	100 devices 70GHz (Laser-Mod) OEIC Int driver/TIA (SiP/InP) 50GHz NRZ/PAM4-16 4" Wafer/fab	1000 devices 100GHz (150Gbps serial) OEIC Int driver/TIA (SiP/InP) 70GHz NRZ/PAM4-16 4 & 6" Wafer/fab	10000 devices 100GHz (150Gbps serial) OEIC Int driver/TIA (SiP/InP) 70GHz NRZ/PAM4-16 4 & 6" Wafer/fab	100,000 devices 100GHz (150Gbps serial) OEIC Int driver/TIA (SiP/InP) 70GHz NRZ/PAM4-16 8" Wafer/fab	100,000 devices 100GHz (150Gbps serial) OEIC Int driver/TIA (SiP/InP) 70GHz NRZ/PAM4-16 8" Wafer/fab
Dielectric Photonics	100 devices 25GHz, 50GHz PIC Tx & Rx NRZ/PAM4 & NRZ/PAM4-8 6" Wafer/fab	1000 devices 70GHz OEIC Int driver/TIA 50GHz NRZ/PAM4-16 8" Wafer/fab	10,000 devices 70GHz OEIC Int driver/TIA 50GHz NRZ/PAM4-16 8 & 12" Wafer/fab	10,000 devices 70GHz OEIC Int driver/TIA 50GHz NRZ/PAM4-16 8 & 12" Wafer/fab	100,000 devices 70GHz (400Gbps) OEIC Int driver/TIA 70GHz NRZ/PAM4-16 15" Wafer/fab	100,000 devices 70GHz (400Gbps) OEIC Int driver/TIA 70GHz NRZ/PAM4-16 15" Wafer/fab
GaAs (VCSEL)	100 devices 25GHz, 50GHz VCSEL PIC 25GHz NRZ/PAM4 & NRZ/PAM4-8 6" Wafer/fab	1000 devices 70GHz VCSEL PIC 50GHz NRZ/PAM4-16 8" Wafer/fab	10000 devices 70GHz VCSEL PIC 70GHz (100Gbps) NRZ/PAM4-16 8" Wafer/fab	10000 devices 70GHz VCSEL PIC 70GHz (100Gbps) NRZ/PAM4-16 8" Wafer/fab	100,000 devices 70GHz (VCSEL-Mod) VCSEL PIC 70GHz (100Gbps) NRZ/PAM4-16 8" Wafer/fab	100,000 devices 70GHz (VCSEL-Mod) VCSEL PIC 70GHz (100Gbps) NRZ/PAM4-16 8" Wafer/fab

Purple brick wall = Technology cost barrier

Tough to design >1600Gbps+ TxRx modules...

Tough to design >70GHz bandwidth devices...

Some technologies have higher performance....

How to scale PIC integration?

Normal Black Font = Reasonably expected based on current efforts
Purple Brick Wall = Technology cost barrier
 Slanted Red Font = Major industry effort required for commercialization

Sources: LWLG, iNEMI, AIM Photonics, Photon Delta

We may have photonics technology → but not at a cost for commercialization...

- Huge amount of data and small font...1-page...
- Details can be better viewed better *online*

Roadmaps provide a vehicle for all stakeholders: Gvt, industry, academia, bankers and investors...

2020 Roadmap	2019	2020	2022	2024	2026	2028
Modules/TxRx Data rate density Form factor	400Gbps 25 Tbps/1U Q/OSFP	800Gbps OSFP/OBO/CP	100Tbps/1U OBO/CP	1600Gbps 400Tbps/1U Co-Pkg/CoB	3200Gbps 1600Tbps/1U Micro-Co-Pkg/CoB	
Typical link reach Ind wish (@400Gbps) Industry plan	<10km \$2/Gbps >\$5/Gbps (<2km)	<10km \$1/Gbps <\$2/Gbps	<2km Purple Brick Wall	<2km \$0.5/Gbps		
Typical link reach Ind wish (@400Gbps) Industry plan	10-100m <\$1/Gbps	5-50m <\$0.5/Gbps	10-100m Purple Brick Wall	<\$0.25/Gbps	<\$0.25/Gbps	<\$0.05/Gbps <\$0.15/Gbps
<i>InP Monolithic</i>	100 devices 25GHz, 50GHz PIC WDM Tx & Rx (30GHz) NRZ/PAM4 3" Wafer/fab	1000 devices 70GHz OEIC Int driver/TIA 50Gbps (50GHz) NRZ/PAM4-8	10000 devices 90GHz OEIC Int driver/TIA 100Gbps (70GHz) Coherent client-side	100000 devices 100GHz OEIC ASIC 50Gbps (50GHz)		
<i>SiP & InP/SiGe hybrid</i>	10 devices 25GHz, 50GHz PIC WDM Tx & Rx (30GHz) NRZ/PAM4 & NRZ/PAM4-8 6" Wafer/fab	100 devices 70GHz (100Gbps) OEIC Int driver/TIA 50Gbps (50GHz) NRZ/PAM4-16	1000 devices 70GHz (400Gbps) Coherent client-side	10,000 devices 70GHz (400Gbps) OEIC Int driver/TIA 100Gbps (serial) Coherent DSP-less		
<i>Polymer Photonics</i>	10 devices 25GHz, 50GHz (Laser-Mod) PIC WDM/MZ Mod Tx & Rx NRZ/PAM4 & NRZ/PAM4-8 3-4" Wafer/fab	100 devices 70GHz (laser-Mod) OEIC Int driver/TIA (SiP/InP) 50GHz NRZ/PAM4-16	1000 devices 100GHz (150Gbps serial) OEIC Int driver/TIA (SiP/InP) 70GHz (serial) Coherent client-side	10000 devices 100GHz (150Gbps serial) OEIC Int driver/TIA (SiP/InP) 70GHz (serial) Coherent client-side	10,000 devices 100GHz (150Gbps serial) OEIC Int driver/TIA (SiP/InP) 70GHz (serial) Coherent client-side	10,000 devices 100GHz (150Gbps serial) OEIC Int driver/TIA (SiP/InP) 70GHz (serial) Coherent client-side
<i>Dielectric Photonics</i>	100 devices 25GHz, 50GHz PIC Tx & Rx NRZ/PAM4 & NRZ/PAM4-8 6" Wafer/fab	1000 devices 70GHz OEIC Int driver/TIA 50GHz NRZ/PAM4-16	10,000 devices 70GHz OEIC Int driver/TIA 50GHz NRZ/PAM4-16	100,000 devices 70GHz (400Gbps) OEIC Int driver/TIA 70GHz		
<i>GaAs (VCSEL)</i>	100 devices 25GHz, 50GHz VCSEL PIC 25GHz NRZ/PAM4 & NRZ/PAM4-8 6" Wafer/fab	1000 devices 50GHz VCSEL PIC 50GHz NRZ/PAM4-16	10000 devices 70GHz (VCSEL-Mod) VCSEL PIC 70GHz (100Gbps) Coherent client-side	100,000 devices 70GHz (VCSEL-Mod) VCSEL PIC 70GHz (100Gbps) Coherent client-side		

Tough to design
>1600Gbps
TxRx modules...

Tough to design
>70GHz
bandwidth
devices...

Some
technologies
have higher
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Normal Black Font = Reasonably expected based on current efforts	Purple Brick Wall = Technology cost barrier	Slanted Red Font = Major industry effort required for commercialization
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Sources: LWLG, iNEMI, AIM Photonics, Photon Delta

Where we penetrate the 'Purple Brick Wall'?

How about a new 1-page roadmap?

- A *1-page PIC packaging roadmap*...
- Details can be better viewed better *online*

Simple 1 slide roadmaps – have impact



1 page roadmap...

Volunteers to critique this 1 pager?
EPIC

2022 Roadmap (PIC Packaging)	2021	2022	2024	2026	2028	2030
Modules/TxRx Data rate density Form factor	400Gbps 25 Tbps/1U Q/OSFP	800Gbps OSFP/OBO/CP	1600Gbps 100Tbps/1U OBO/CP	400Tbps/1U Co-Pkg/CoB	1600Tbps/1U Micro-Co-Pkg/CoB	3200Gbps
Typical link reach Ind wish (@400Gbps) Industry plan	<10km \$2/Gbps >\$5/Gbps (<2km)	<10km \$1/Gbps <\$2/Gbps	<2km Purple Brick Wall	<2km \$0.5/Gbps Purple Brick Wall	<2km \$0.5/Gbps	<2km \$0.2/Gbps
Typical link reach Ind wish (@400Gbps) Industry plan	10-100m <\$1/Gbps	5-50m \$1/Gbps <\$0.5/Gbps	Purple Brick Wall	<\$0.25/Gbps Purple Brick Wall	1-25m \$0.25/Gbps	<\$0.05/Gbps <\$0.15/Gbps
Traditional Gold Box	Butterfly 50GHz. Form factor: PIC chips <10 functions	100GHz micro-butterfly 10-50 functions	Purple Brick Wall	nano-butterfly 150GHz	200GHz	500 functions
Surface mount	SOIC (<50 lead) 25GHz. Connectorized SM/MM fiber Flip-chip bumping to pcb <100 bumps Thermal passive heat management	50GHz Fiber ribbons 1x12/24	micro-SOIC (<50 lead) 70GHz <250 bumps advanced thermal designs	70GHz (100Gbps NRZ) 2D fiber ribbons 2x24/48 <1000 bumps	100GHz (130Gbps NRZ) 2D fiber ribbons >500 fibers <10,000 bumps	100GHz (130Gbps NRZ) 2D fiber ribbons >500 fibers <10,000 bumps
Chip-on-board & waferscale	Flip-chip bump (100) Interconnect bandwidth 25GHz. Wafer format 150mm Fiber to PIC packaging (grating/edge) 2D Integration	1000 devices 50GHz 200mm micro-optics to PIC packaging (grating/edge) 2.5D integration	10000 devices 70GHz	300mm 3D integration	100,000 devices 100GHz Interposer to PIC packaging (edge/evanescent)	200GHz 450mm
Co-packaging (layer 1 – chip on carrier)	2 chips 25GHz. 2D Integration (electronic IC on PIC) Active cooling (standard TEC) Passive cooling (std heat spreaders)	10 chips 50GHz 2.5D integration (electronic IC and PIC on carrier) Customized TEC/controller	30 chips 70GHz Graphene based materials	70GHz micro-TEC pkg with FIC Integrated with PIC Pkg.	50 chips 150GHz PIC on interposer (Optical) TEC integrated directly PIC Integrated with PIC	50 chips 150GHz PIC on interposer (Optical) TEC integrated directly PIC Integrated with PIC
Co-packaging (layer 2 -	10 devices 25GHz. Single die Optical platform 150mm Electronic and photonic PIC 2D package	50GHz twin die multiple die 2D Optical platform 200mm electronic and photonics PIC 2.5D package	100 devices 70GHz multiple die 3D/fan out interconnect optical platform 300mm	1000 devices 150GHz multiple die 3D/double sided PIC 3D package platform	1000 devices 150GHz multiple die 3D/double sided PIC 3D package platform	1000 devices 150GHz multiple die 3D/double sided PIC 3D package platform
	Normal Black Font = Reasonably expected based on current efforts		Purple Brick Wall = Technology cost barrier		Slanted Red Font = Major industry effort required for commercialization	

A PIC Packaging roadmap...

Source: Lightwave Logic, EPIC



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European observations...



- USA
 - Large silicon foundry platform with government funds
 - Suitable for defense contractors, and large corporations
 - InP PICs with Infinera, Lumentum, II-VI
- Japan and Asia
 - Huge silicon foundries hungry for silicon photonics (TSMC, Hisilicon, Samsung etc.)
 - Suitable for large companies with SiPh platforms
 - InP PICs with Fujitsu, NTT, Sumitomo
- Europe...
 - Has a mix of large and small foundries all hungry for PIC leadership...
 - EU has deep experience with PICs...

SME = Small and medium size enterprise

How does Europe win with PICs?

Nurture and grow PIC platforms...

- EU has made broad investment into PIC photonics R&D last 30years
 - There has been early focus on PIC InP/SiPh/hybrid core competency
- Today → EU has PIC pilot lines in Europe
 - Small focused PIC photonic teams → *that can scale to manufacturing, and self-sustainability*



Foster these types of projects to commercialization...hub-spoke architecture...

- How to win?
 - *Provide easier access for SMEs...they drive innovation...*
 - Create a sharper focus on *hybrid PIC performance/foundry* & packaging (co-packaging, chip-scale), PIC design infrastructure, EU PIC manufacturing.
 - Create more PIC pilot line scale projects...that impact growing markets (Auto, medical, sensing, display etc.)

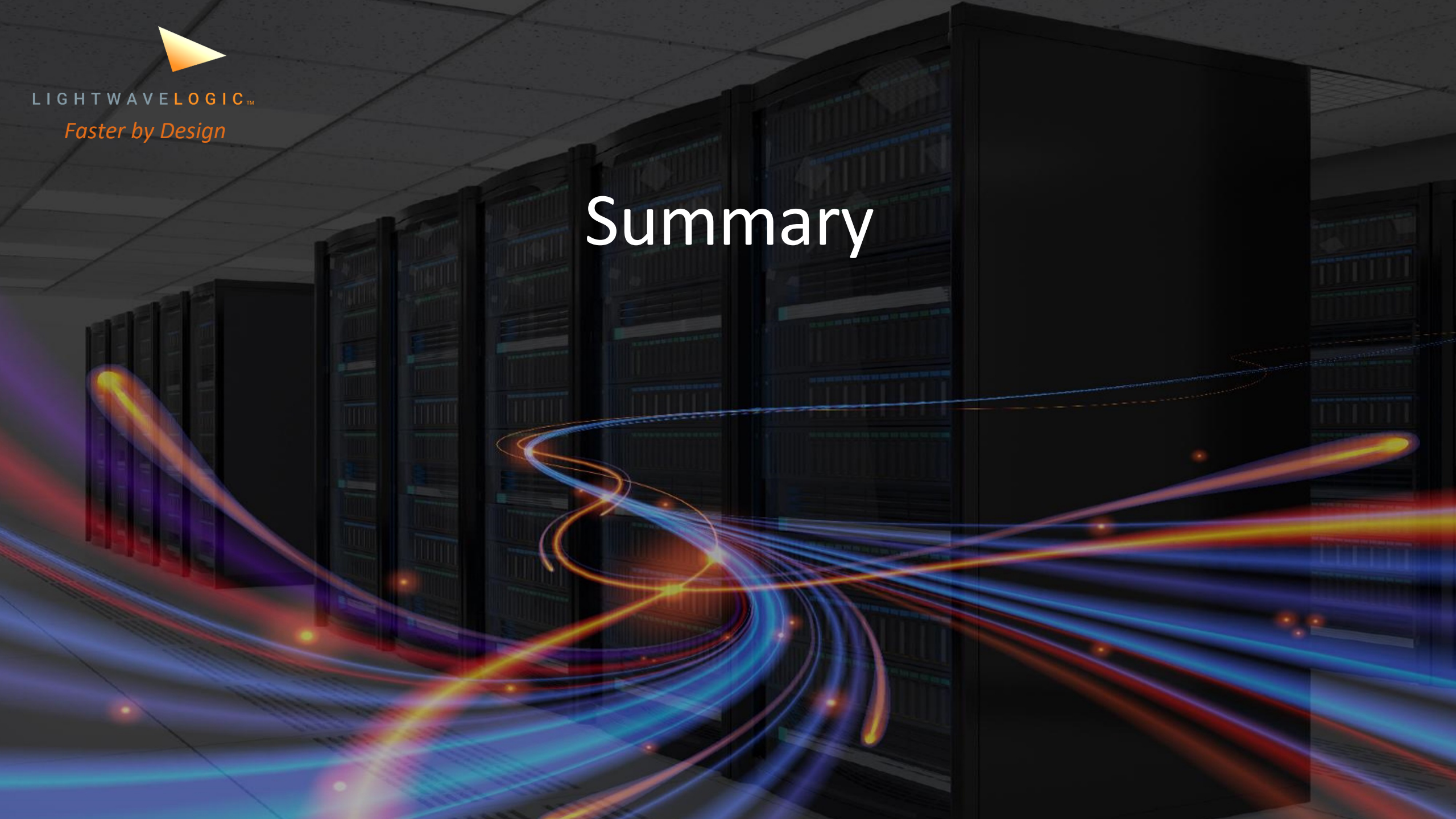
Build into a global center of excellence...



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Faster by Design

Summary



3 takeaways to remember today...

- Will PIC photonics enable many things and will it be part of our lifestyle?
 - **YES!...from 'heavy data' today for virtual working to enabling new market opportunities: consumer, health, bio, defense, display, lighting, automotive...**
- Will photonics be integrated – just like ICs 50years ago and become the engine for new designs?
 - **Absolutely...it will be the next generation IC...the PIC**
- Will integrated photonics (PICs) enable new products?
 - **Of course!...and the applications are broad and exciting**

Why drive a horse buggy when the motor car is available?