LIGHTWAVE LOGIC

Faster by Design

Utilizing foundries to scale hybrid electro-optic polymer modulators

Michael Lebby, CEO & Dr. John Zyskind, VP Engineering

Lightwave Logic (NASDAQ:LWLG)

Safe harbor

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We are excited…

Ringing the Bell at NASDAQ (10th Sept 2021)

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Organic up-list…as promised in 2017…

NASDAQ 1yr Anniversary

1st Sept 2022: 1yr on NASDAQ

Source: NASDAQ


4 takeaways…

Takeaways

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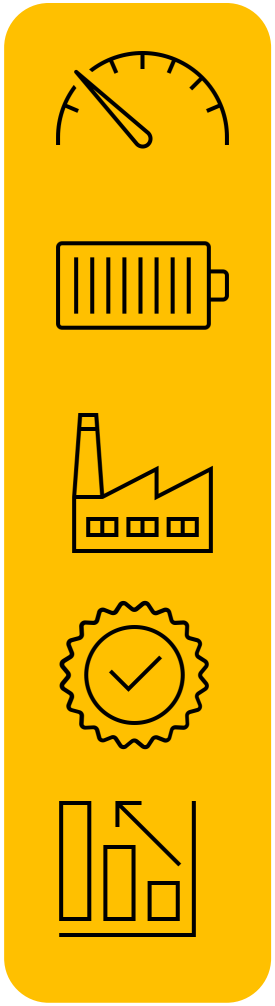
- We have unique polymers…
- Our technology is ultra-fast, ultra-low power…
- We are positioned to have polymers become ubiquitous…
- Polymers are foundry compatible…


Unique core
competences

Polymer advantages

- Naturally very fast at switching light (material properties)
  - 2-3X existing solutions using modulators
- Naturally very low power consuming (material properties)
  - 10X lower power depending on device/architectural design
- Easily fabricated using CMOS/Silicon foundries
  - Process is standard and does not require special tool kits
  - Consistent, stable and reliable poling process
- EO Polymer has security of supply and scalable in vol
  - Material designed and sourced directly from LWLG
- Low-cost addition to integrated photonics platforms
  - Silicon photonics can be boosted in performance

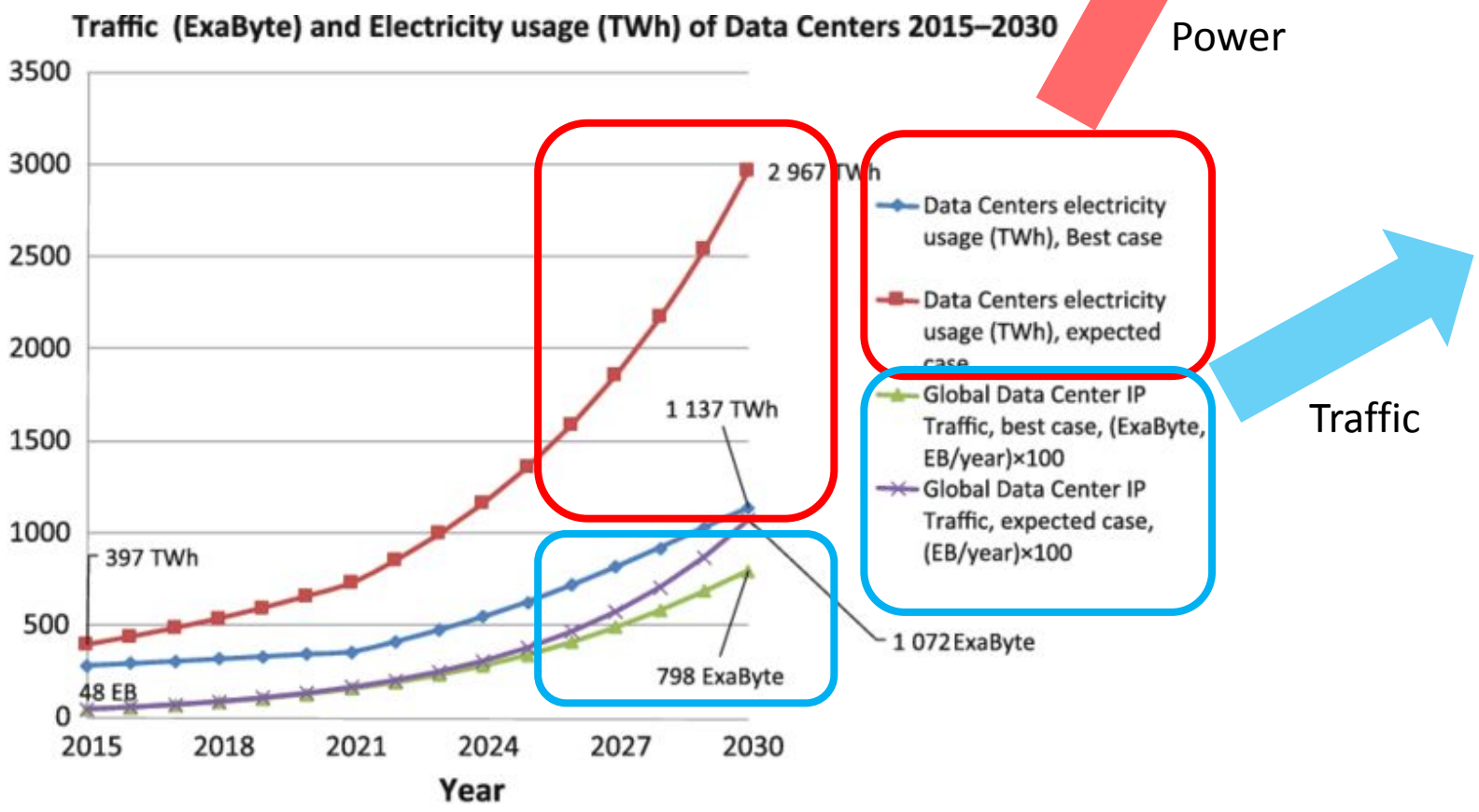


Polymers are unique in their properties

Source: Lightwave Logic (LWLG)


Market dynamics

…Yet Power Consumption Spiraling Up



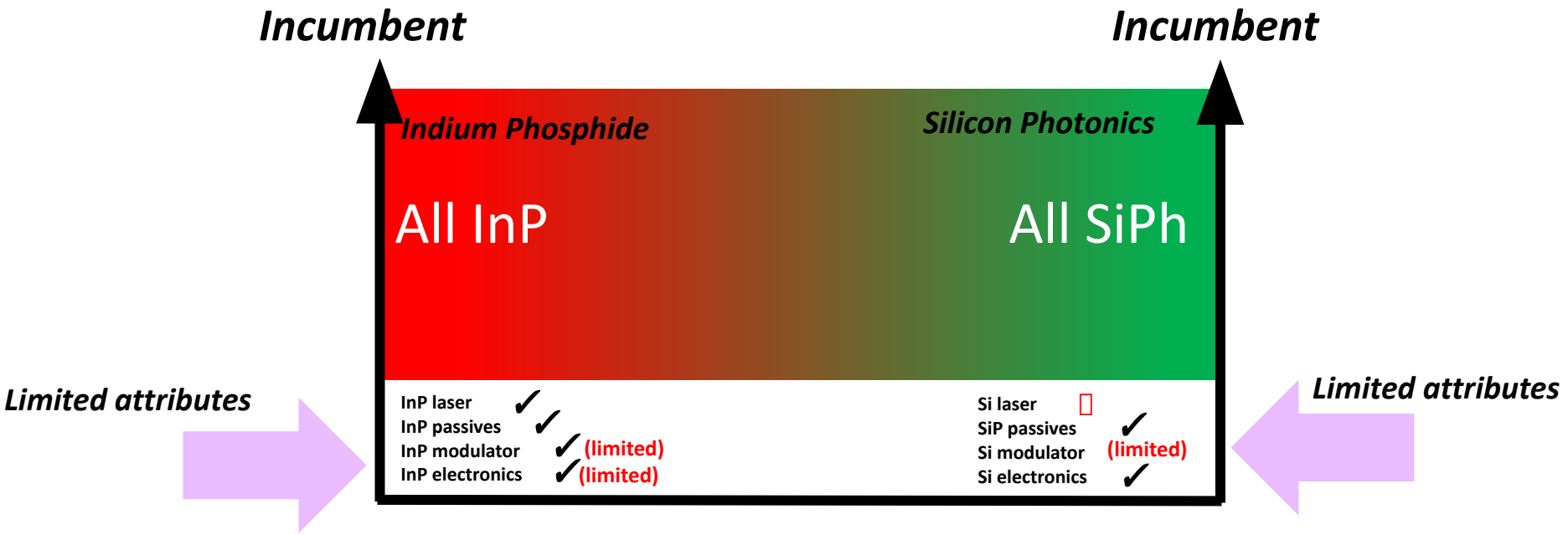
Major challenge for DCs and service providers

Power is growing exponentially with increased traffic levels…it is the Achilles Heel…

Source: Publication: Walnum, HJ et al


Hybrid PIC…

Fiber communications have 2 incumbent PICs, however…



Incumbent technologies can't do everything monolithically…

Source: LWLG

Hybrid PICs increase performance…

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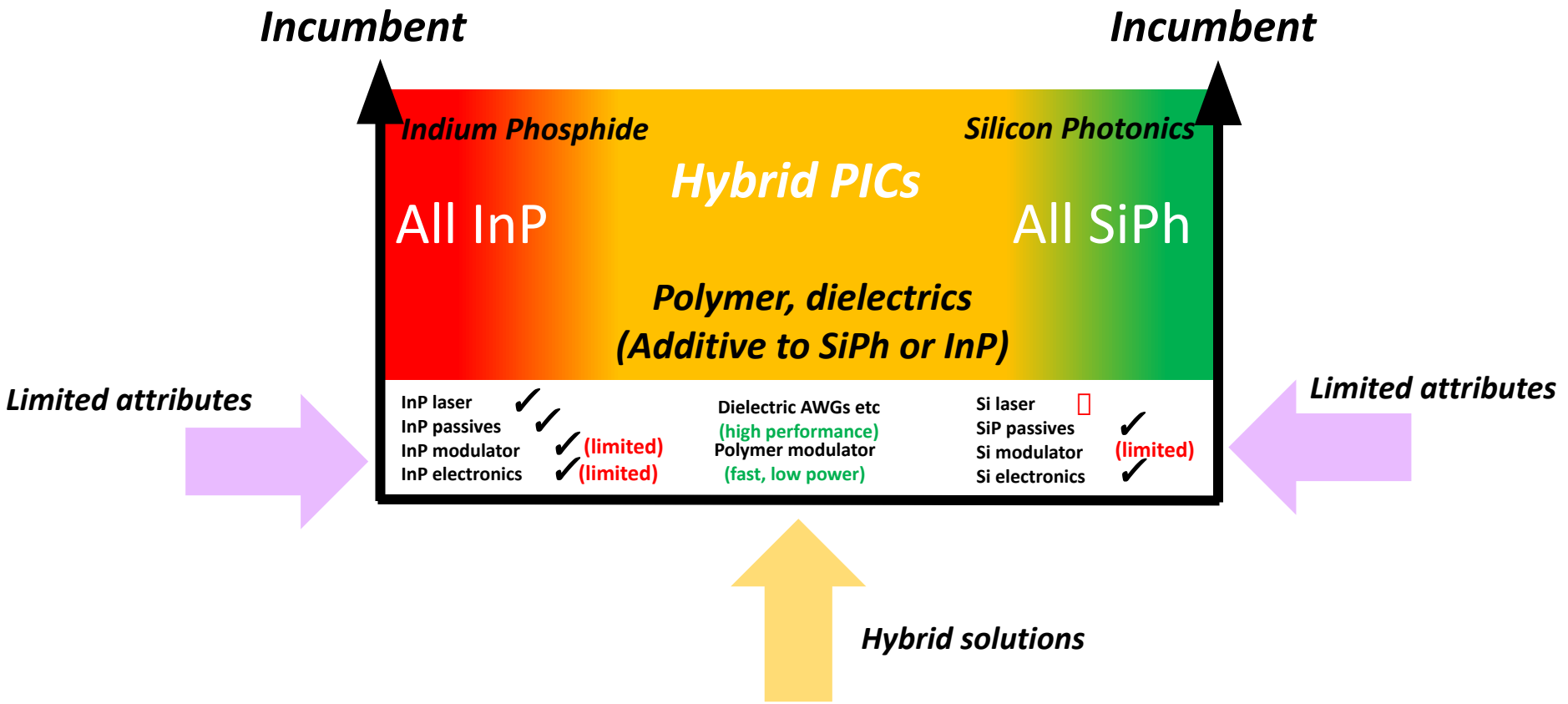
New hybrid PICs



Hybrid PICs can boost performance of PICs

Source: LWLG

Trend towards hybrid PICs…

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- PIC incumbent platforms:
  - InP (Indium Phosphide) □ e.g. Hybrid PIC □ InP + Si ICs
  - SiPh (Silicon photonics) □ e.g. Hybrid PIC □ SiPh + InP Laser
  - GaAs (Gallium Arsenide) □ e.g. Hybrid PIC □ GaAs + Si ICs

- ***New platforms for Hybrid PICs***
  - *Polymers (modulators)*
  - *Dielectrics (passives)*
  - *Silica (passives)*
  - *Glass (passives)*
  - *Thin Film Lithium Niobate (TFLN) (modulator)*
  - *Metal/plasmonic, (modulator)*
  - *Barium titanate (BTO) (modulator)*
  - *Germanium (detector)*
  - *Gallium Nitride (GaN) (LEDs)*
  - ***Many others…***

Mix and match to optimize the best performance…

Source: LWLG

Representative PIC actors…

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- 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

Source: Yole

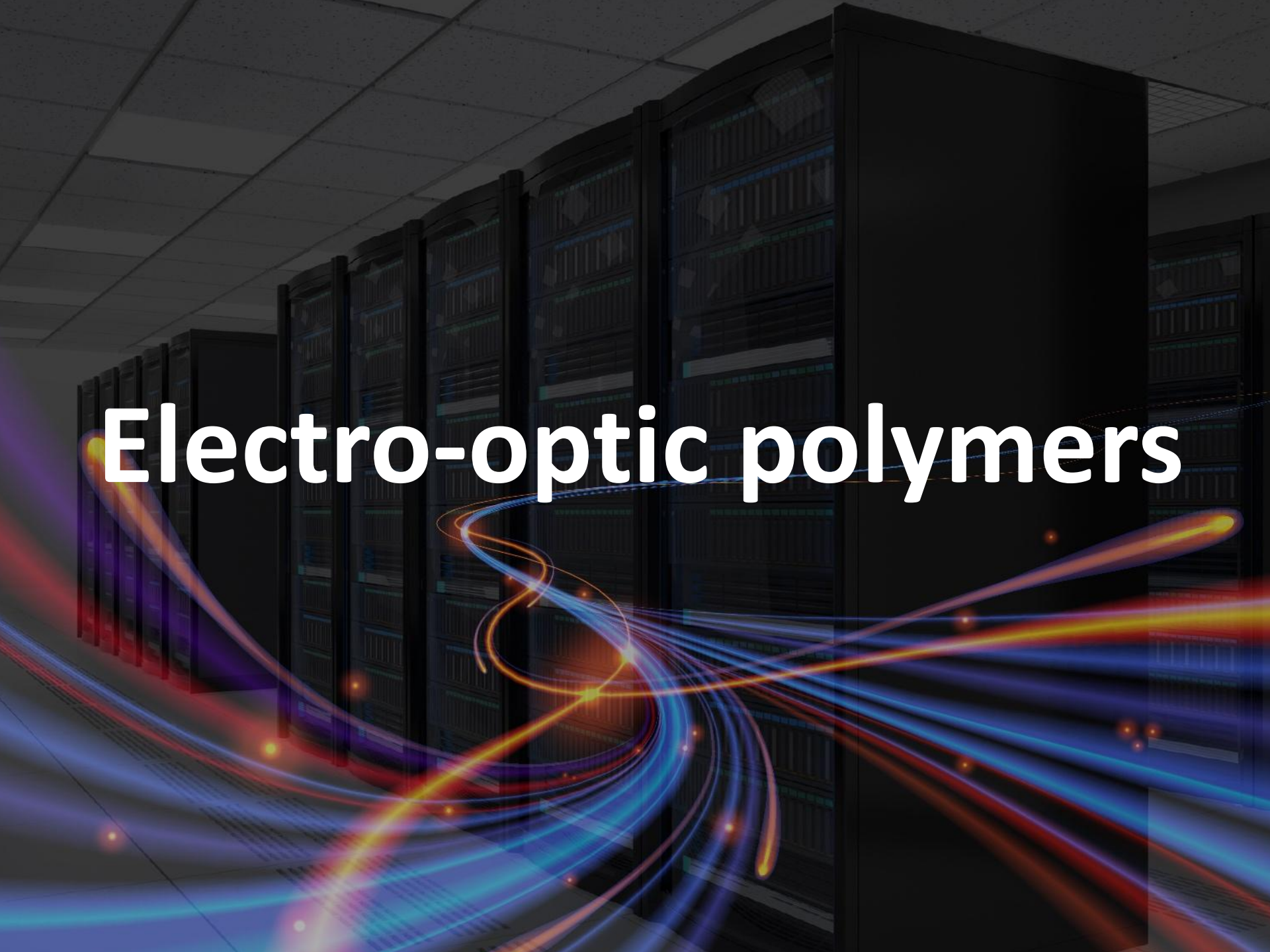

Foundry compatible?

Foundry compatibility for PICs

New technology	Foundry compatibility
Polymers (modulators)	Silicon, InP, GaAs, others
Dielectrics (passives)	Silicon, InP, GaAs, others
Silica (passives)	Silicon, InP, GaAs, others
Glass (passives)	Silicon, InP, GaAs, others
Thin Film Lithium Niobate (modulators)	LiNoB, silicon (?)
Metal/plasmonic (modulators)	Silicon, InP, others
Barium Titanate (modulators)	Silicon (?)
Germanium (detectors)	Silicon, GaAs
Gallium Nitride (LEDs, lasers)	GaN, silicon (?)
Graphene (detectors)	Silicon (?)

Silicon and InP offers best opportunities to scale volume quickly and efficiently

Source: LWLG


Electro-optic polymers

Natural integration with big foundries

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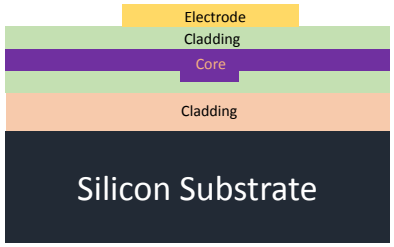
Additive to semiconductor platforms (SiPh, InP…) to enhance performance

Polymer Stack™

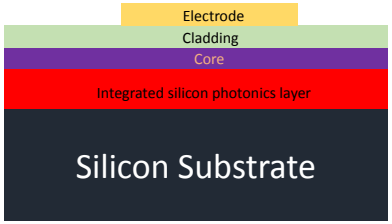


Classic!

Polymer stack modulator

- 3-layer polymer stack waveguides
- Excellent high-speed performance and high stability.
- Standard fab equipment & methods

Polymer Plus™

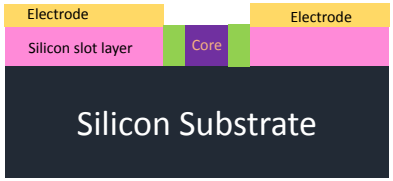


Additive!

Simpler and easier to integrate

- Minimizing polymer layers for integration of modulator with other devices in Si (or other) PIC platform
- Natural integration with PDK of silicon foundries

Polymer Slot™



Tiny!

Polymers in Si slot modulators

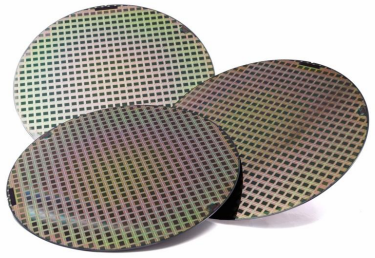
- Small size for highest integration levels
- Natural integration with PDK of silicon foundries

Turbo-charge your silicon photonics & integrated photonics with polymers…


Foundry scaling

Partnering for success

- Partnering with multiple foundries, packaging partners and module/transceiver partners to position LWLG for future high-volume production
- Partnering to qualify polymer Process Development Kits (PDK) with foundries using standard fabrication techniques
- Technology evaluation & feedback
- Partnering for licensing the use of polymer materials that have been sourced, supplied and manufactured by LWLG
- Partnering for technology transfer of fabrication and device design to manufacturing facilities and foundries



Partnering allows us to focus on our uniqueness, efficient use of capital, & to prepare for volume…

Source: Global Foundries, IMEC

Volume scale with silicon foundries *with timelines*

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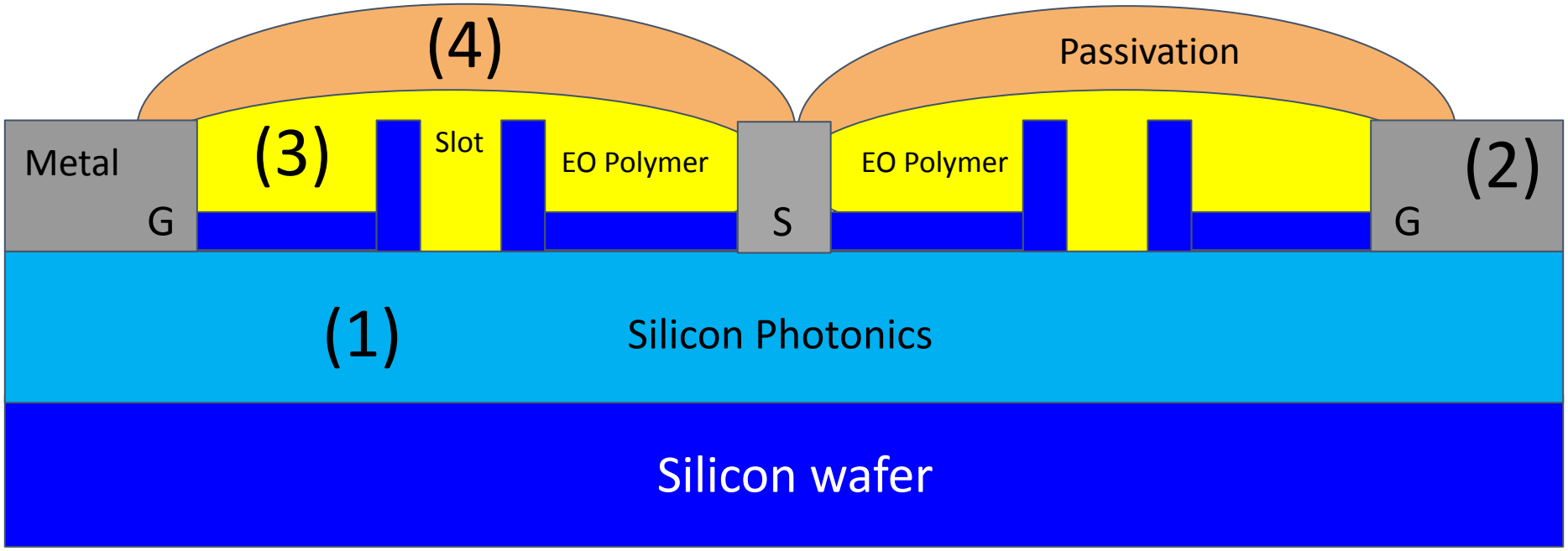
Foundry	Geographical location	Wafers	Existing PIC PDK (silicon photonics, InP)	Open to create EO polymer PDK	Expected results
Foundry A (polymer plus)	North America	Silicon	Yes	In progress	2H22-1H23
Foundry B (polymer plus)	North America	Silicon	Yes	In progress	2H22-1H23
Foundry C (polymer plus)	Europe	Silicon	Yes	In progress	2H22-1H23
Foundry D (polymer slot)	North America	Silicon	Yes	In progress	2H22
Foundry E (polymer slot)	Europe	Silicon	Yes	In progress	2H22
Foundry F (polymer slot) – in discussion	North America	Silicon	Yes	Planned	2023
Foundry G (polymer slot) – in discussion	Europe	InP	Yes	Planned	2023
⋮					

Deep activities with foundries for volume scaling

CMOS/silicon compatible PDK □ Polymer Slot™

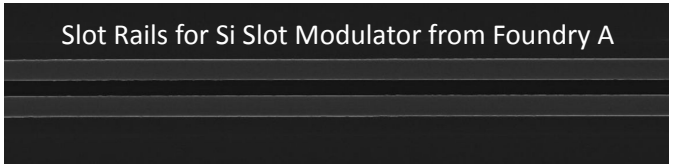
- (1) Standard CMOS/silicon photonics chip with slots defined by photolithography
- (2) Standard metallization for gate/source contacts
- (3) Spin-on EO polymer, cured in standard ovens, polled for optical switching
- (4) Dielectric passivation for protection to environment (chip-scale packaging)
- (5) Standardized, consistent poling process with extremely high yields

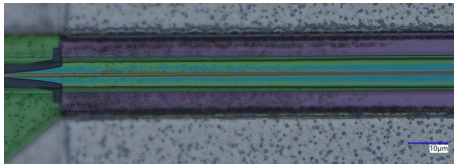


Standard silicon fabrication processes; standard silicon tools

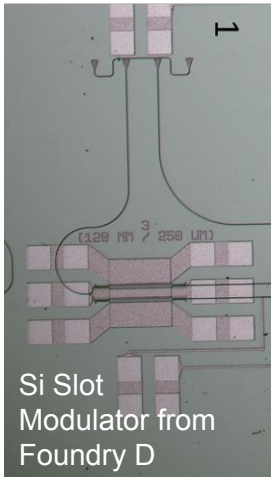
Source: Lightwave Logic (LWLG), PDK = Process Development Kit

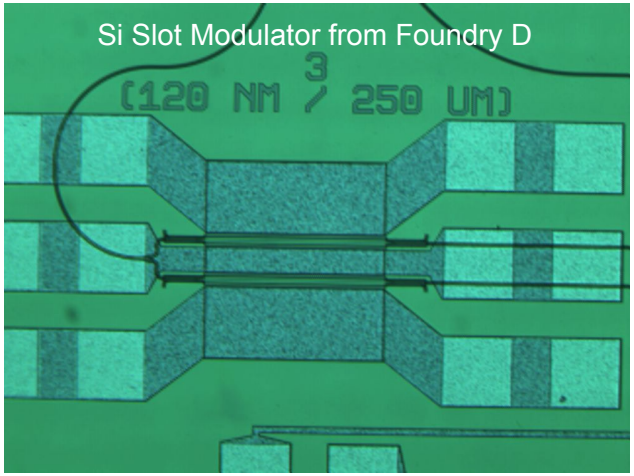
Foundry fabrication with PDK

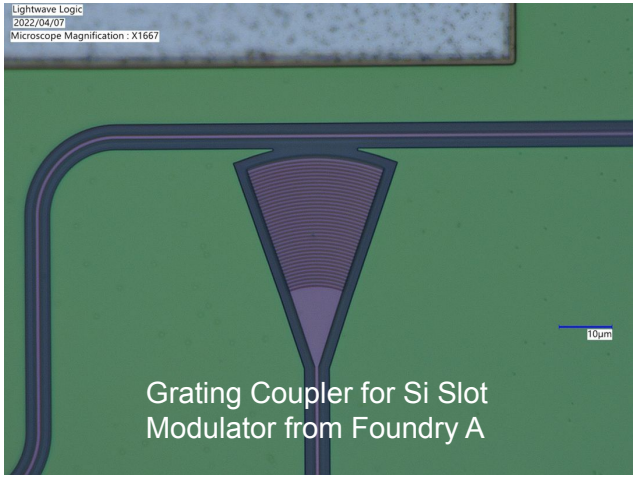


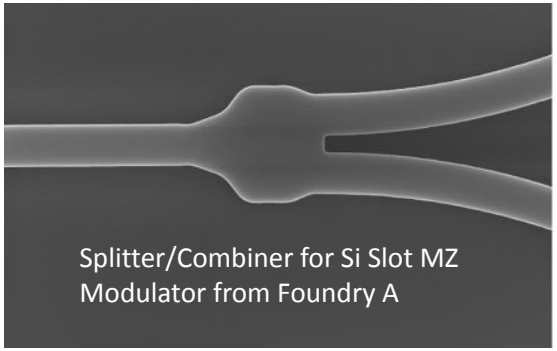


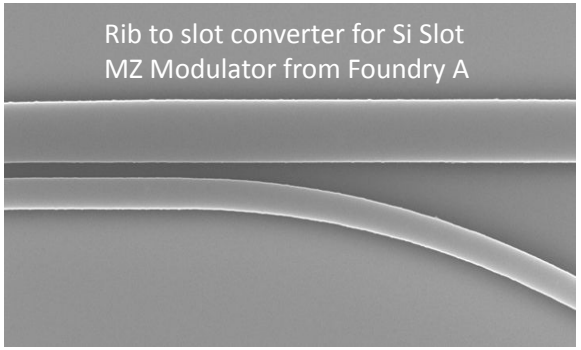
Optical Microscope image of strip to rib converter + slot waveguide from Foundry D







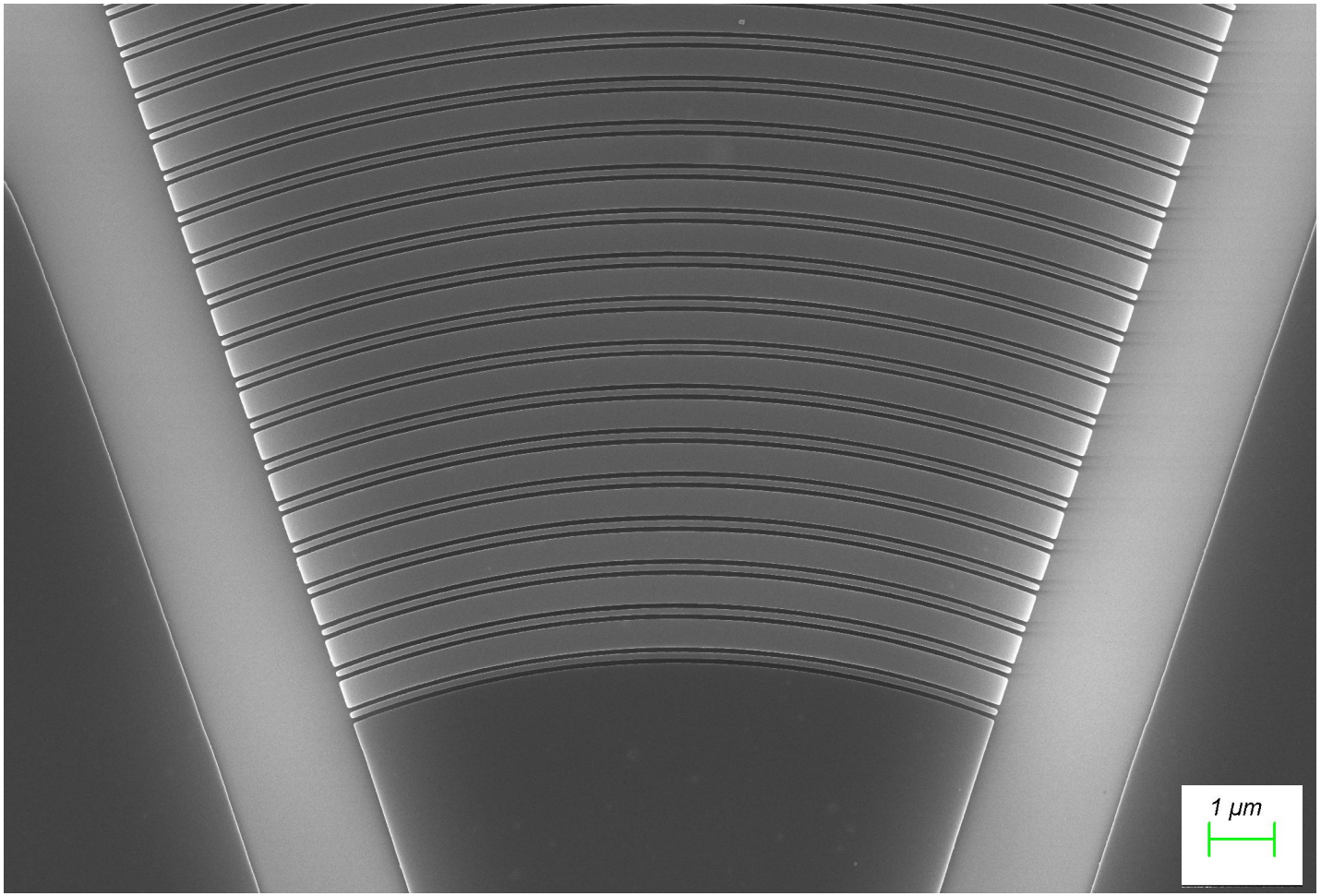




Standard silicon fabrication components…

Source: Lightwave Logic (LWLG)

Foundry fabrication



Vertical grating coupler example

Source: Lightwave Logic (LWLG)

Polymer slot – foundry processing

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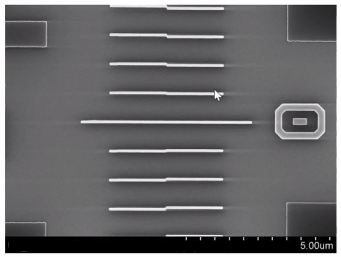
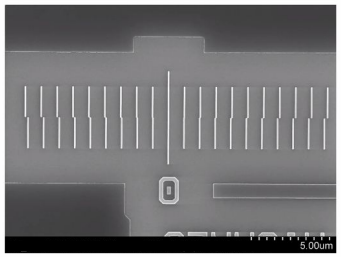
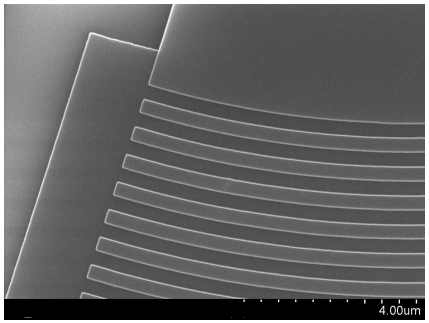
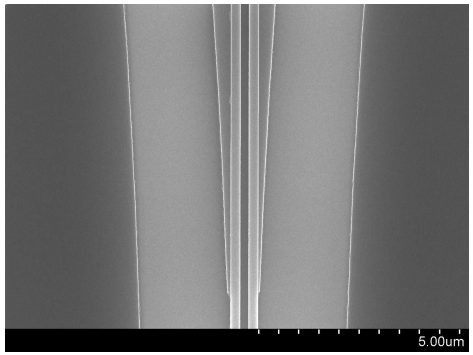
Pilot Wafer SEM Images





Verniers: better than 20 nm alignment





Grating Couplers and straight waveguides with good (standard) roughness and Strip-to-slot converters with good definition

Foundry quality, alignment, fabrication

Poling for foundries

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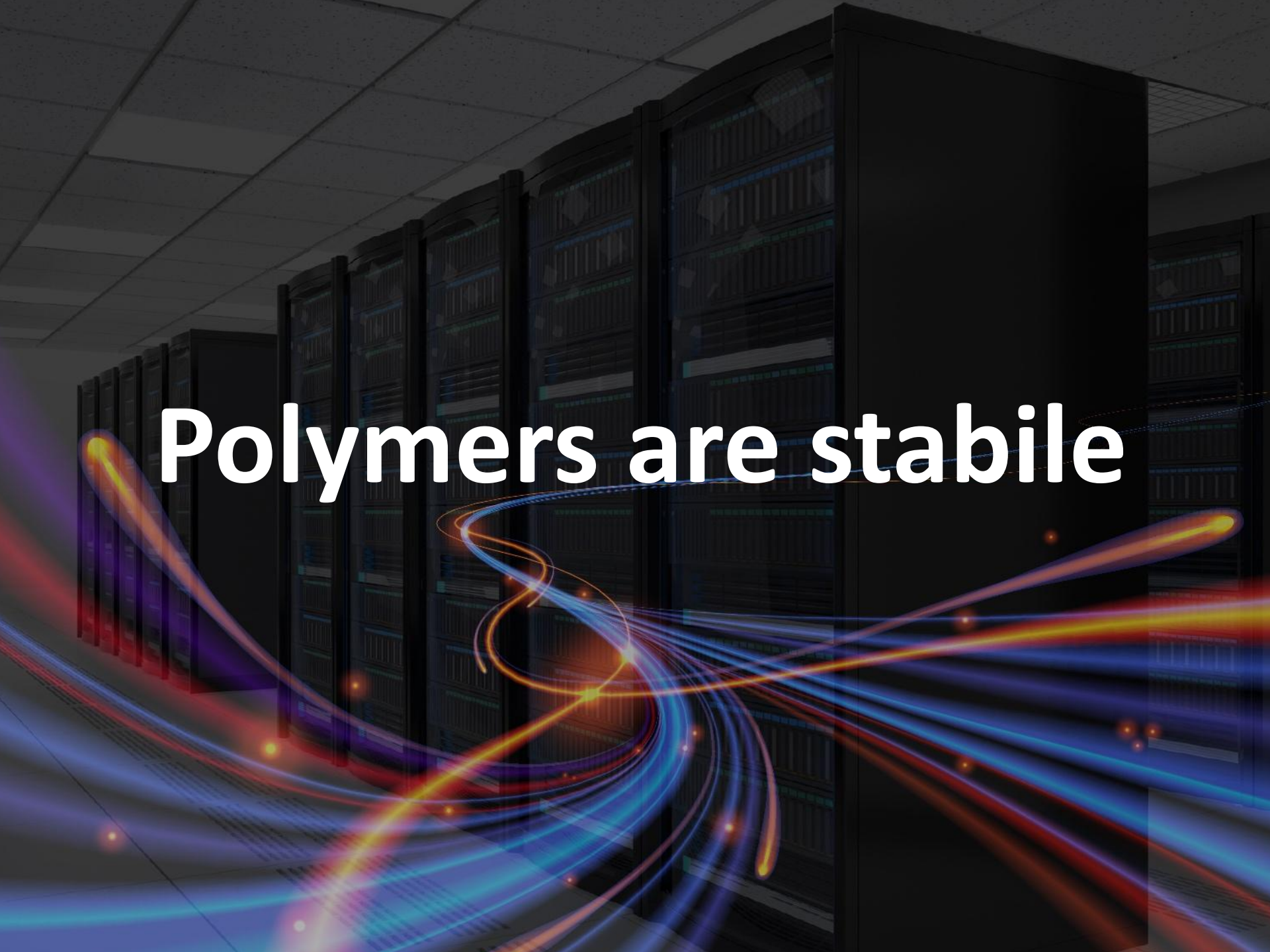
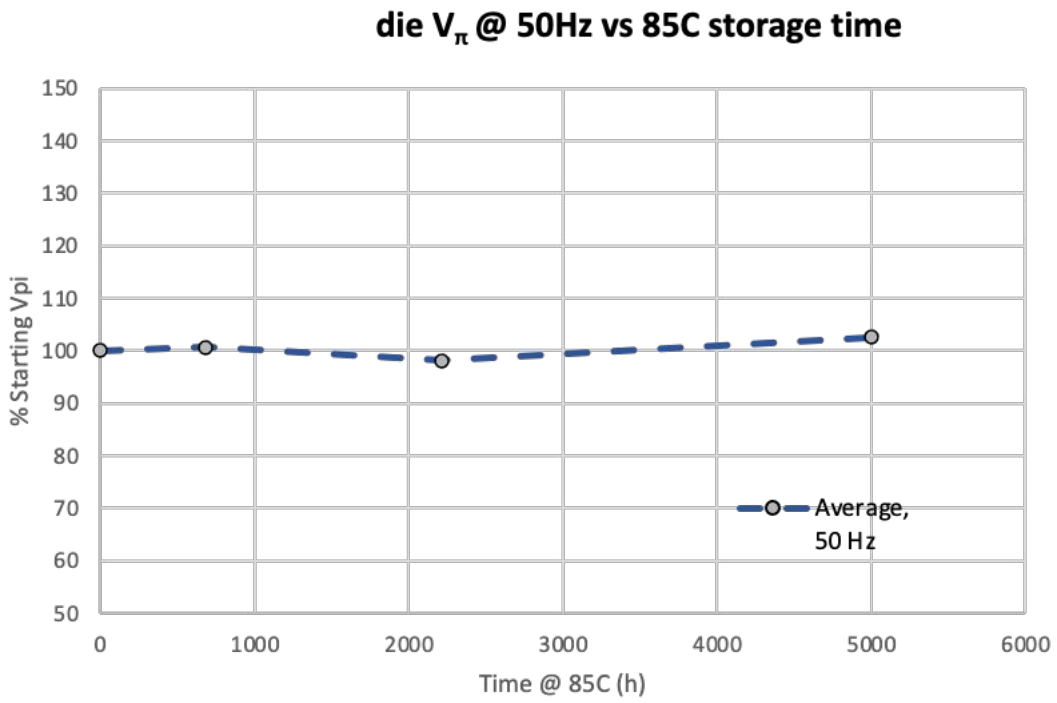
- Unique EO performance of poled polymers
  - For example: Bandwidths in excess of 100GHz, phase velocity match allowing bandwidths of 170GHz+, Low Vpi, High r33…
- Polymers are stable and reliable
  - The same arguments were made against LCDs and OLEDs and now we use OLED TVs, mobile displays….and we never discuss stability, reliability issues today…ever…
- Today, poling is a process that is consistent, stable and reliable and suitable for foundry operation
  - Advanced process, excellent control, standardized technique
  - Extremely high yields on >1000 poled devices…

Poling can be ported to foundries to simplify PDK processes


Polymers are stabile

Stability of polymers

- 3 layer-stack devices
- Over 5khrs stability @ 85C
- Voltage delta <5% @ 1kHz for continuous change

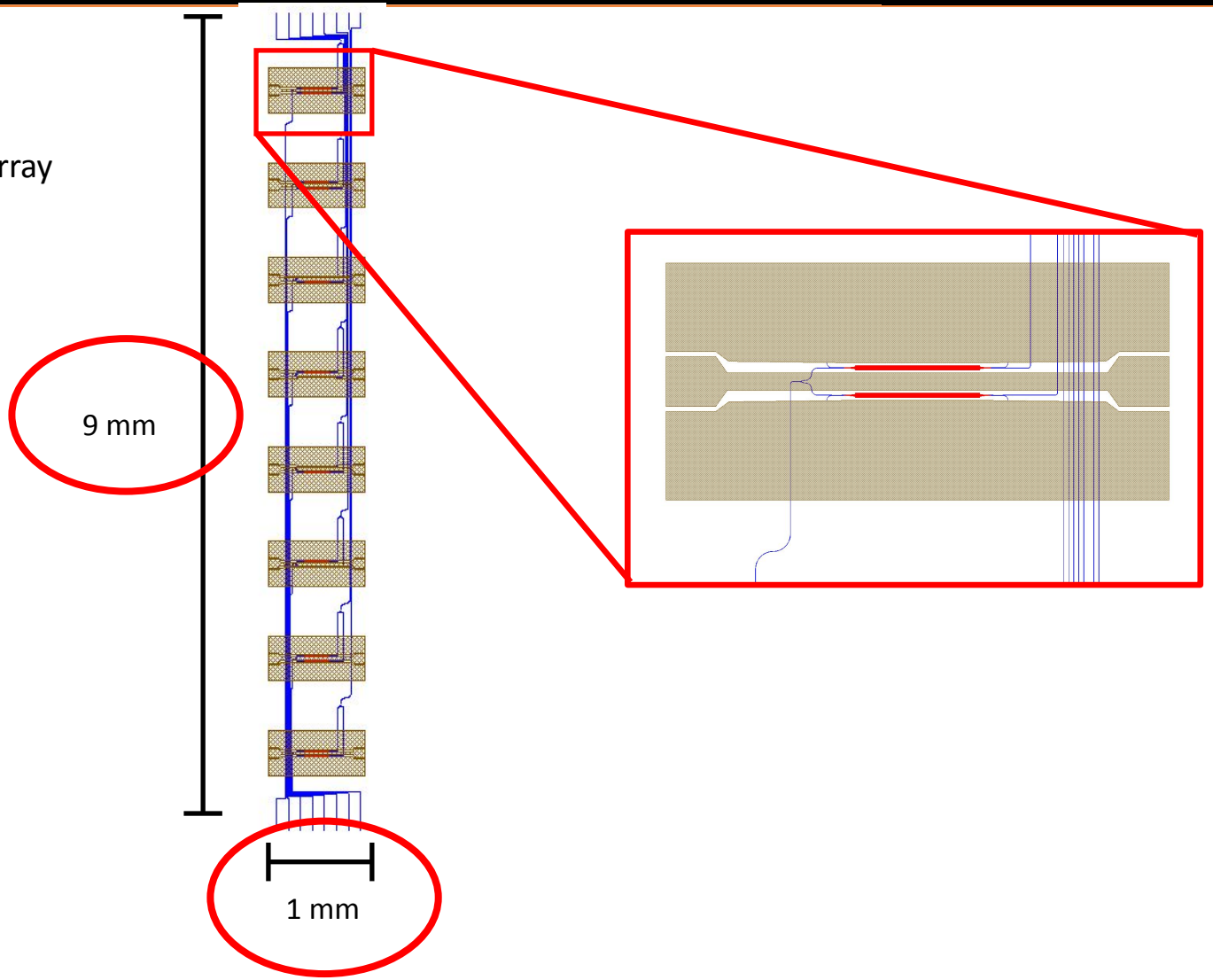


Polymer modulator chip stability >5kHrs


Polymers modulators are tiny…

Polymer slot modulators are very small

LWLG
8 x 1 Polymer Slot™ array



Size matters!

Source: Lightwave Logic (LWLG)

Only 30X better*…

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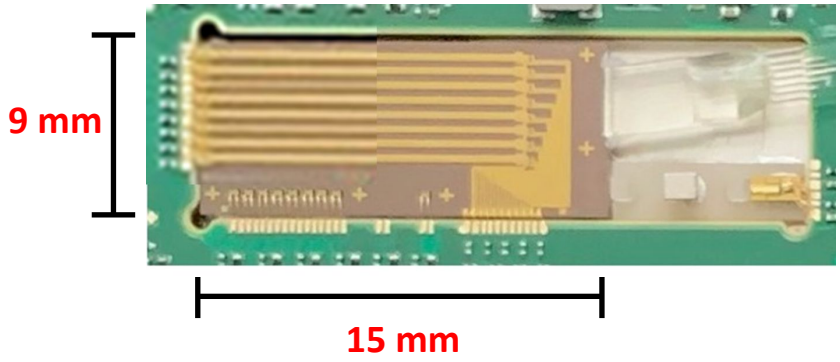
Competitive transceiver

TFNL 800G-DR8 Module



8 modulators x 100G = 800G or 0.8T

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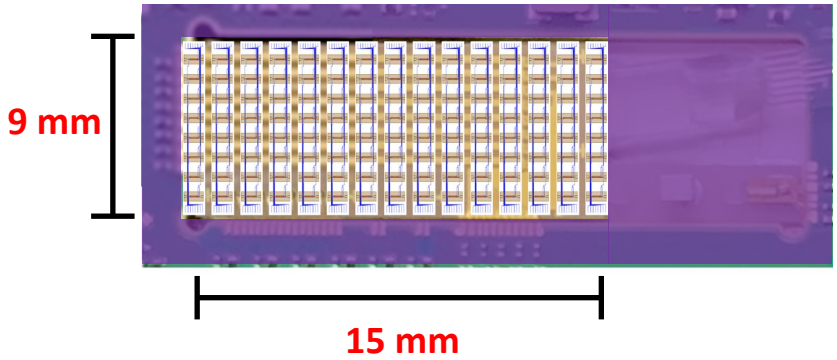
Polymer Slot™



120 modulators x 100G = 12T
120 modulators x 200G = 24T

Potential for 30x data capacity in same pluggable formfactor

At least 30X better than competition…size, low power, and speed matter…

*Source: Lightwave Logic (LWLG), Hyperlight (2022); *Density can be increased a factor of 2 giving ~60X capacity improvement towards 50T*


Breaking the speed limit…

Historical perspective

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1G: 1 lane x 1G
(1990s)

Easy

10G: 1 lane x 10G
(circa 1999-2000)

Easy

40G: 4 lane x 10G
(early 2000s)

Tougher

100G: 4 lane x 25G
(early 2010s)

Difficult

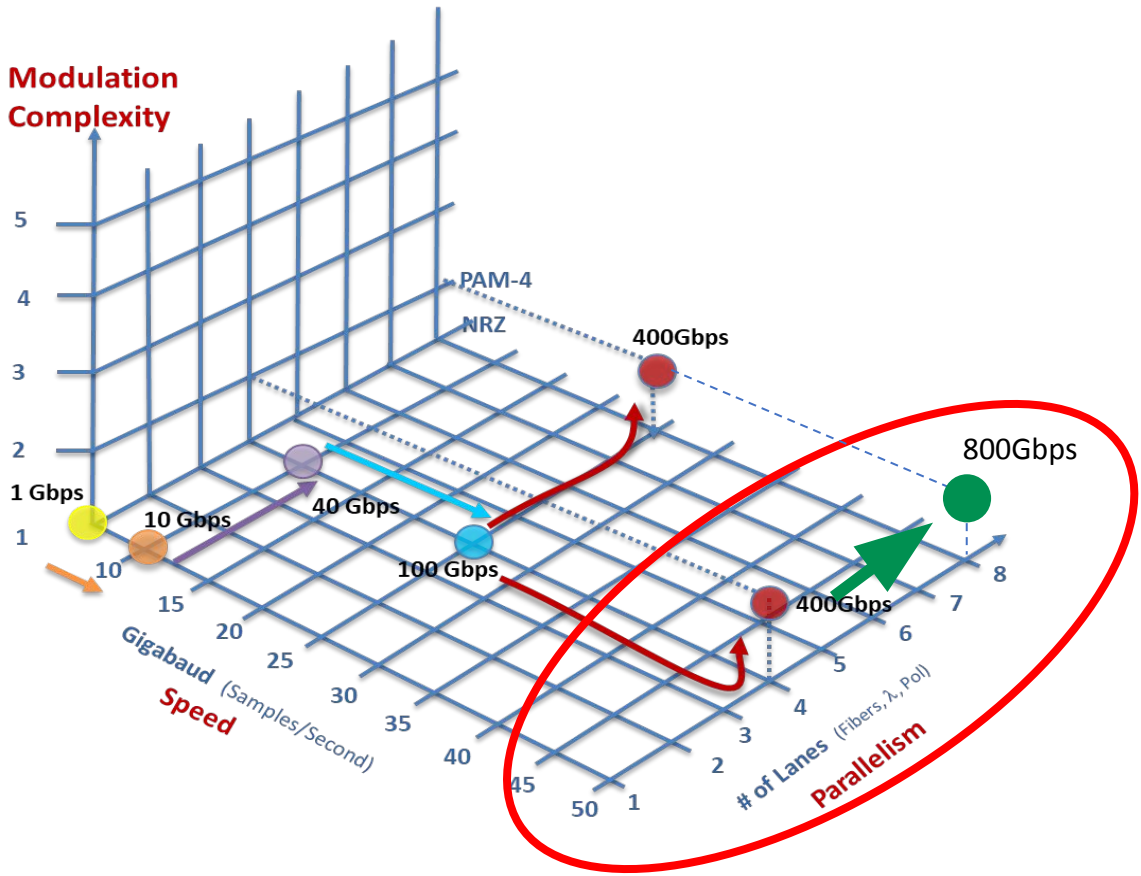
400G: 4 lane x 50G PAM4
400G: 8 lane x 25G PAM4
(2015 onwards)

More difficult

800G: 4 lane x 100G PAM4
800G: 8 lane x 50G PAM4
(2022 onwards)

Much more difficult

1600G: 8 lane x 100G PAM4



Increasing data rates becomes more and more difficult…

Sources: Lightwave Logic (LWLG) research and motivation from Ethernet Alliance

Traffic capacity: road analogy

Good roads: Faster cars: more traffic capacity

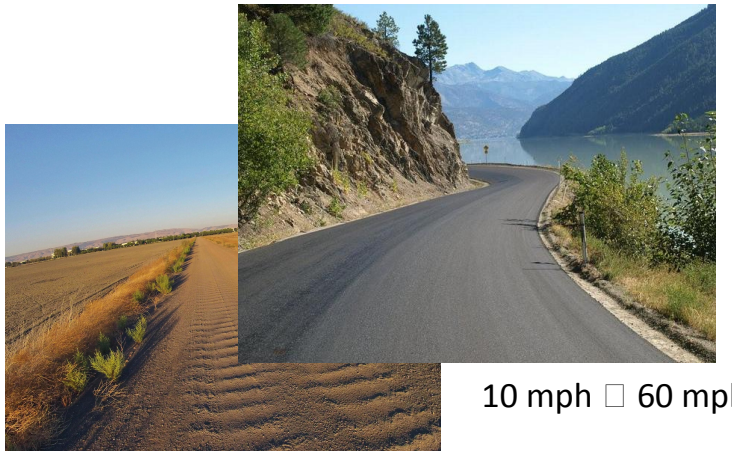
More lanes: more traffic capacity

We already did the easy things like paving the road, and adding more lanes (WDM)…

Traffic handling: road analogy

Industry has done the hard stuff like ‘encoding’ and ‘higher order modulation’

What about speed?



10 mph 60 mph

Still ~60 mph

Speed has hit a plateau…

Speed limited by conventional photonics

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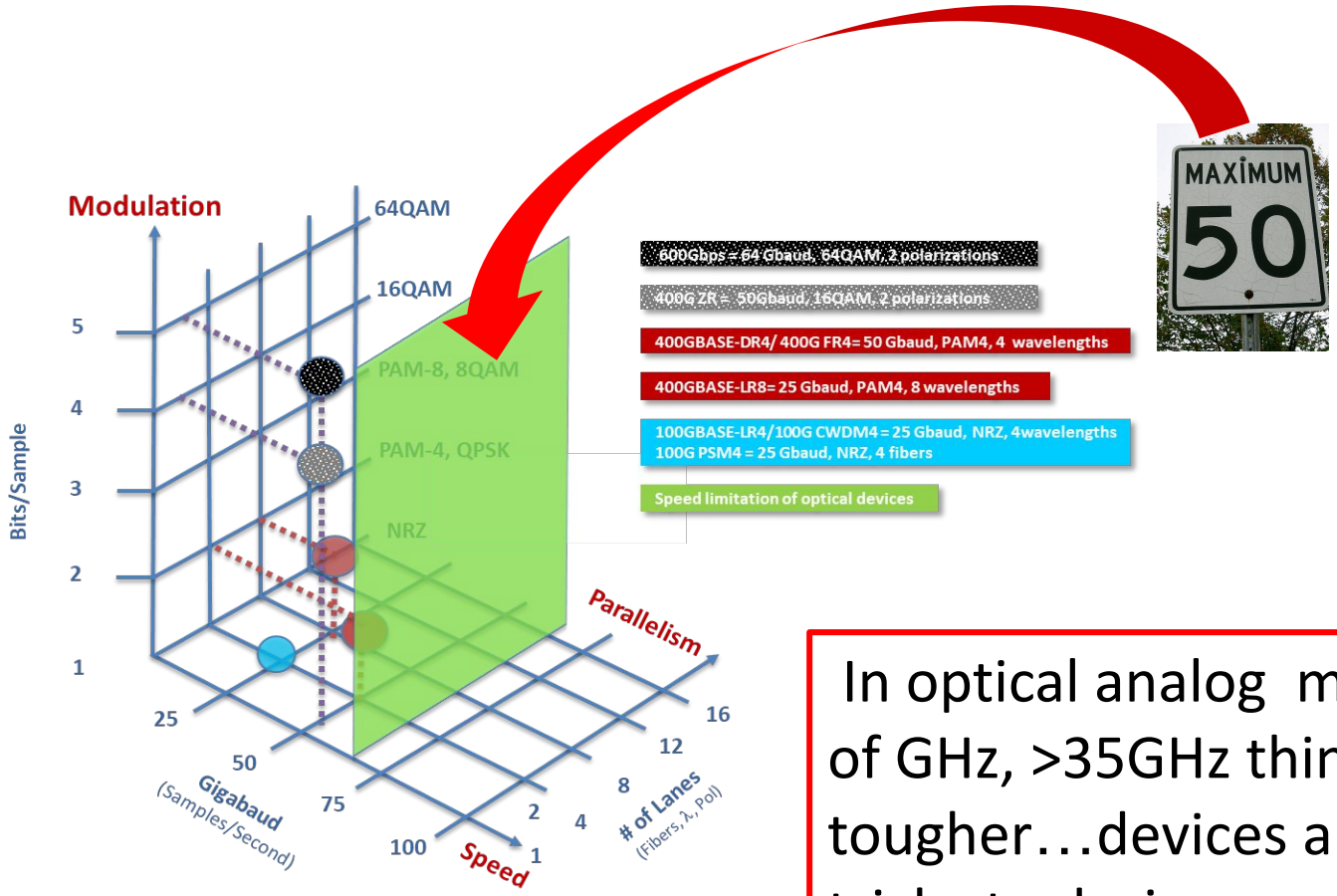

In optical analog metrics of GHz, >35GHz things get tougher…devices are tricky to design

Speed limited in optical devices by device physics…requires innovation…

Super high optical bandwidth modulators

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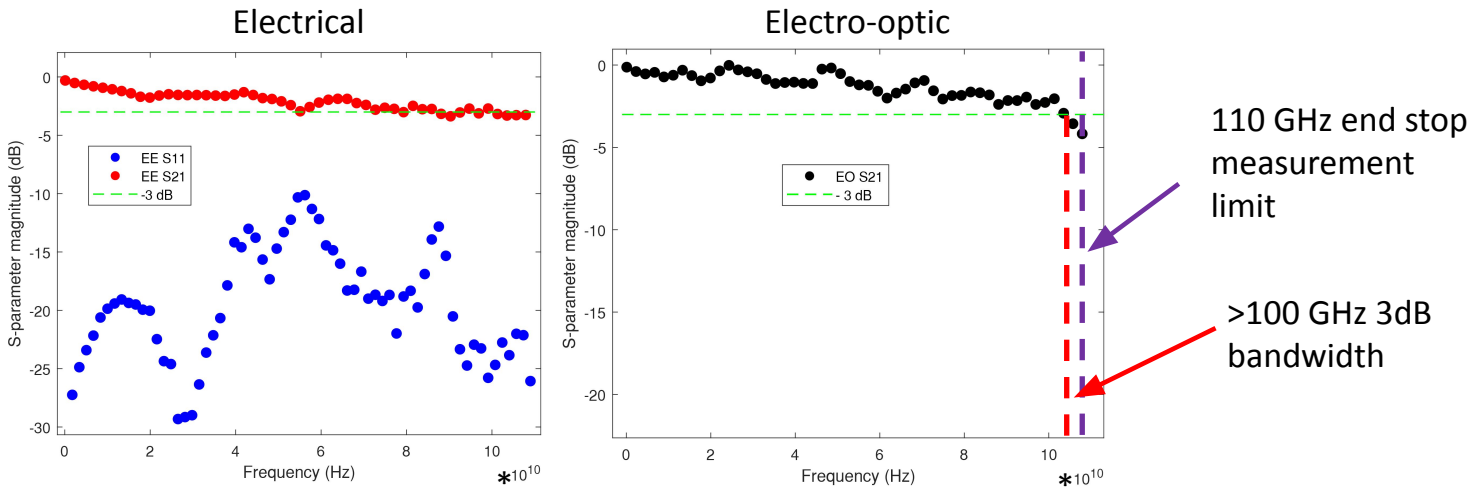
Recent high-frequency S-parameter data from polymer modulators



Super high performance > 100GHz S21 EO 3dB bandwidth

Source: LWLG

Ultra-fast polymers break the speed limit…

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Polymers increase data rates as their bandwidths are 70GHz, 100GHz and beyond…

The holy grail….single lane

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Single lane…have to have faster optics…

Source: Ethernet Alliance, OSFP MSA

Our polymers break through the *speed wall*

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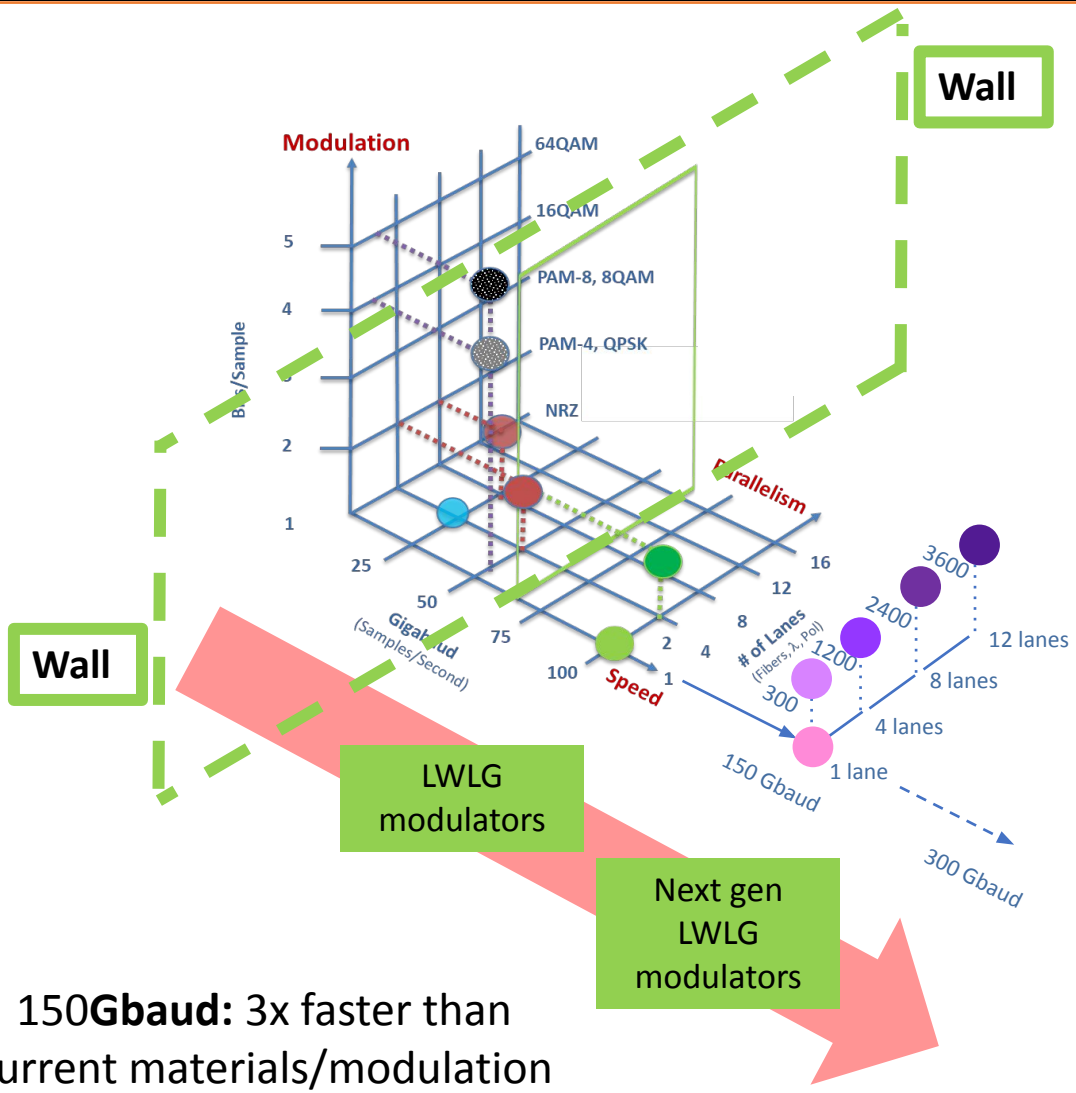

150**Gbaud:** 3x faster than current materials/modulation

Data rates after breaking through the wall…

- 100Gbps = 100Gbaud, NRZ, 1 lane
- 800Gbps = 100Gbaud, PAM4, 4 lanes
- 150Gbps = 150Gbaud, NRZ, 1 lane
- 300Gbps = 150Gbaud, PAM4, 1 lane
- 1200Gbps = 150Gbaud, PAM4, 4 lanes
- 2400Gbps = 150Gbaud, PAM4, 8 lanes
- 3600Gbps = 150Gbaud, PAM4, 12 lanes

Ultra-fast speed…

Sources: Lightwave Logic (LWLG) research and motivation from Ethernet Alliance

Polymer engines…

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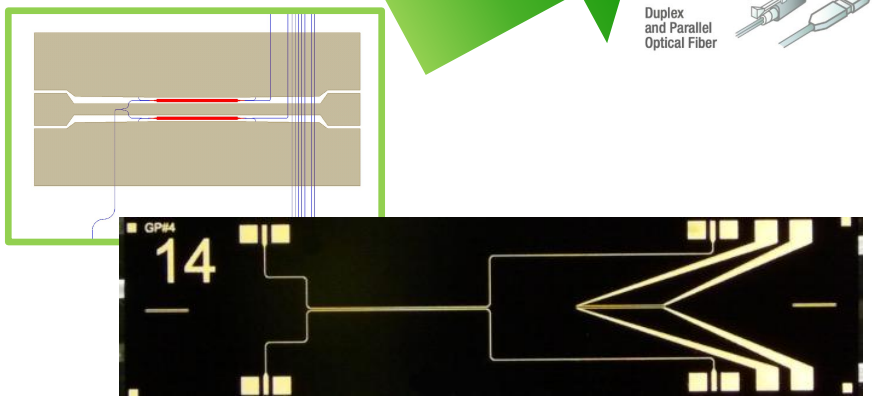
Polymer modulators fabricated in silicon foundries



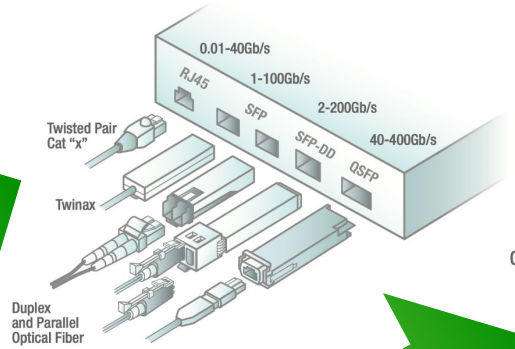
FORM FACTORS

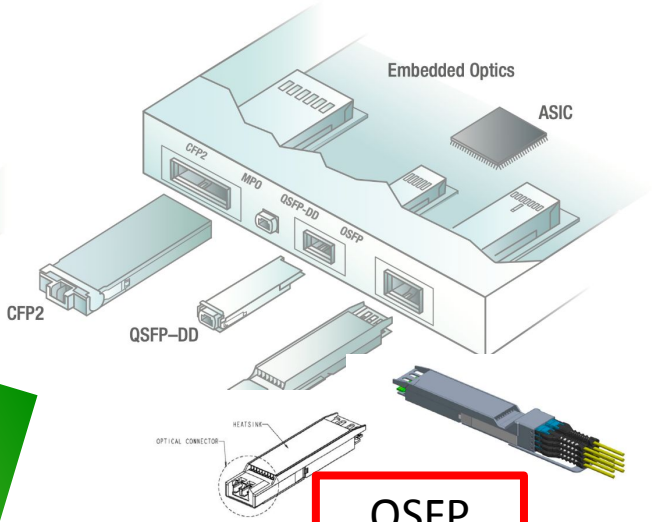
This diagram shows the most common form factors used in Ethernet ports. Hundreds of millions of RJ45 ports are sold a year while tens of millions of SFP and millions of QSFP ports ship a year.

This diagram shows new form factors initially designed for 100GbE and 400GbE Ethernet ports.

1–4 Lane Interfaces

4+ Lane Interfaces



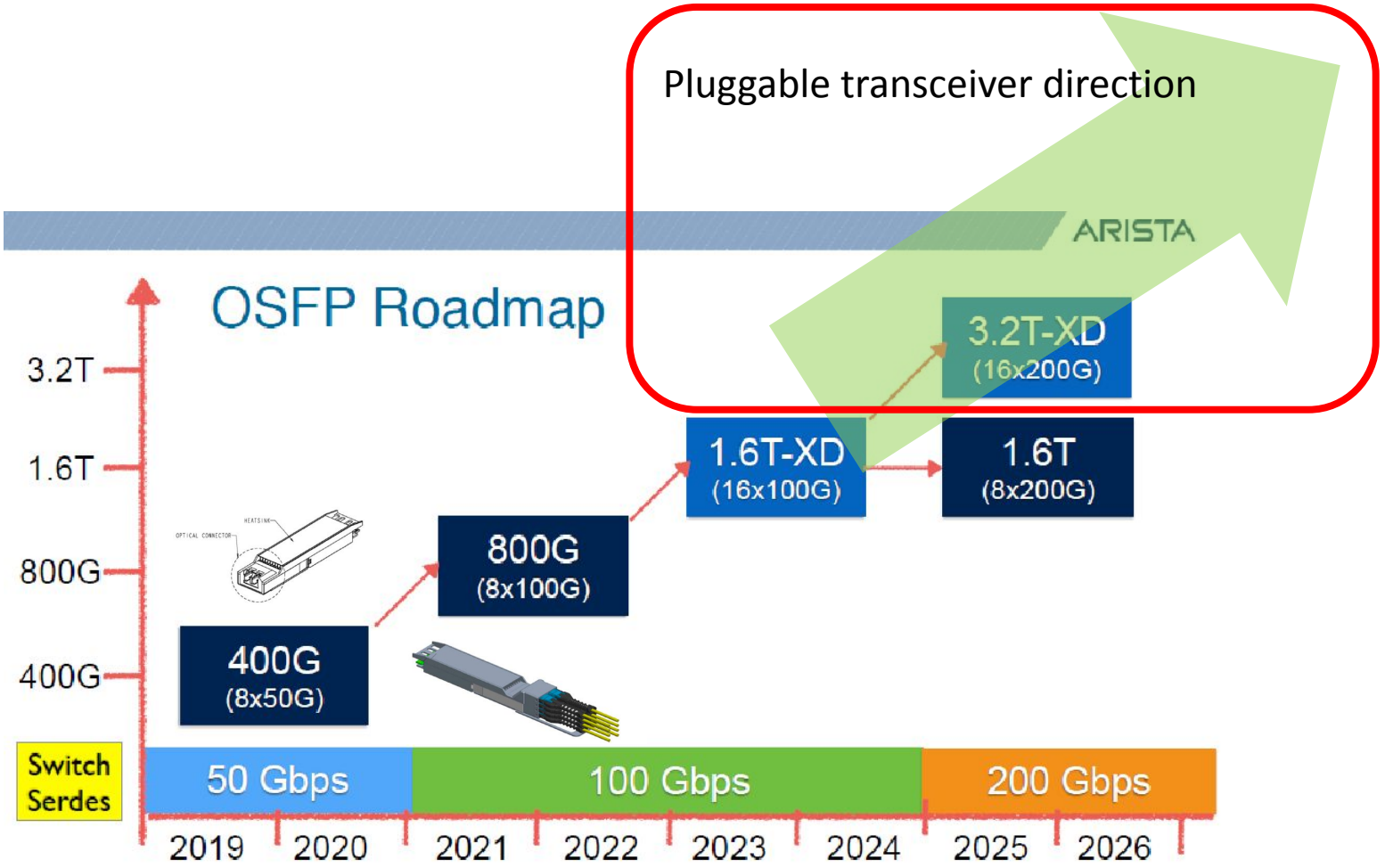


OSFP

Polymer engines for pluggable transceivers

Source: Ethernet Alliance, OSFP MSA

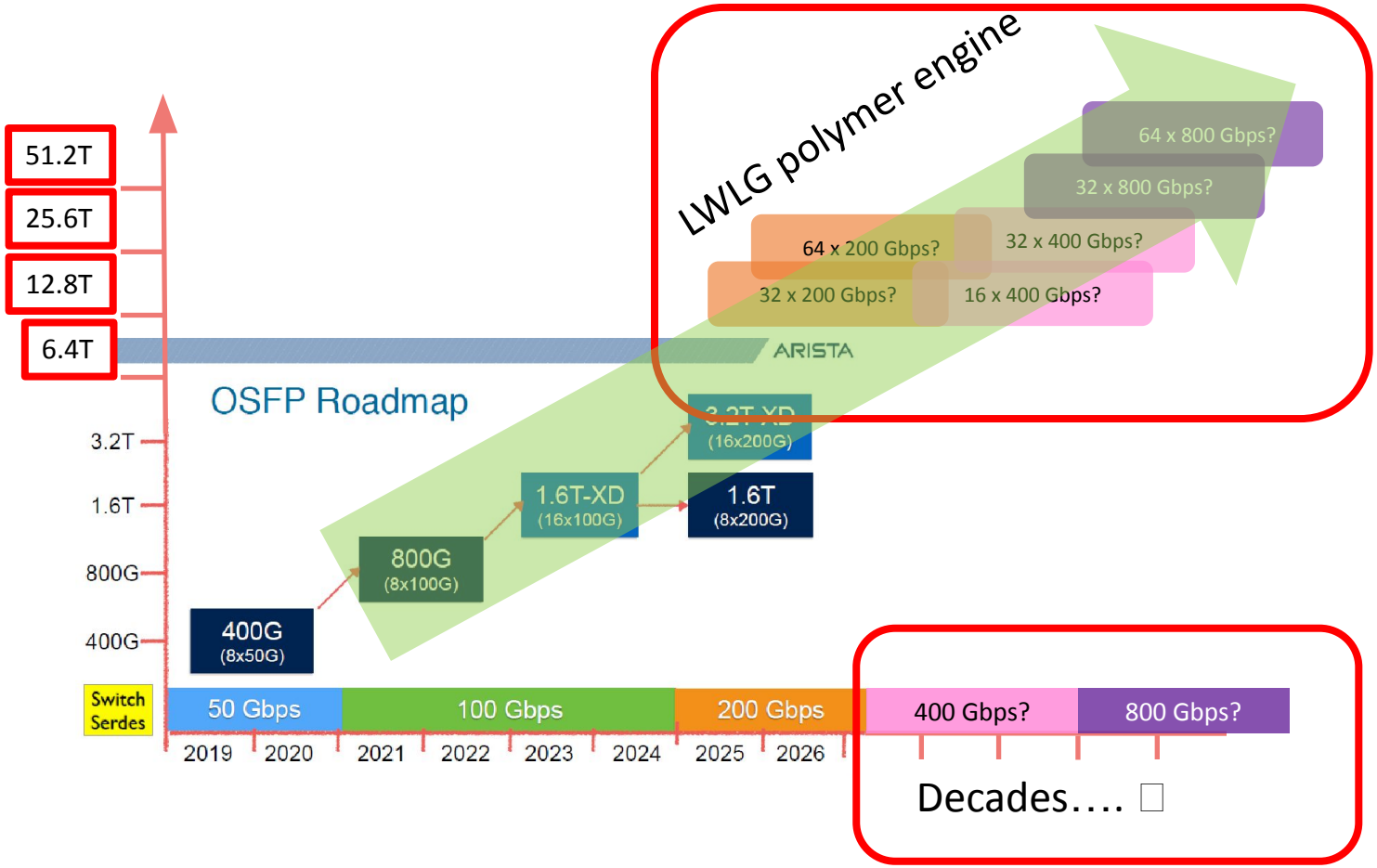
Optical transceiver trends



Pluggable transceivers need to increase in speed in conjunction with the electronics

Source: Adapted from Arista (2022), Lightwave Logic (LWLG), OSFP MSA (2022)

Polymer engine roadmap…



Roadmap enabled by high speed, low power, tiny footprint polymers…

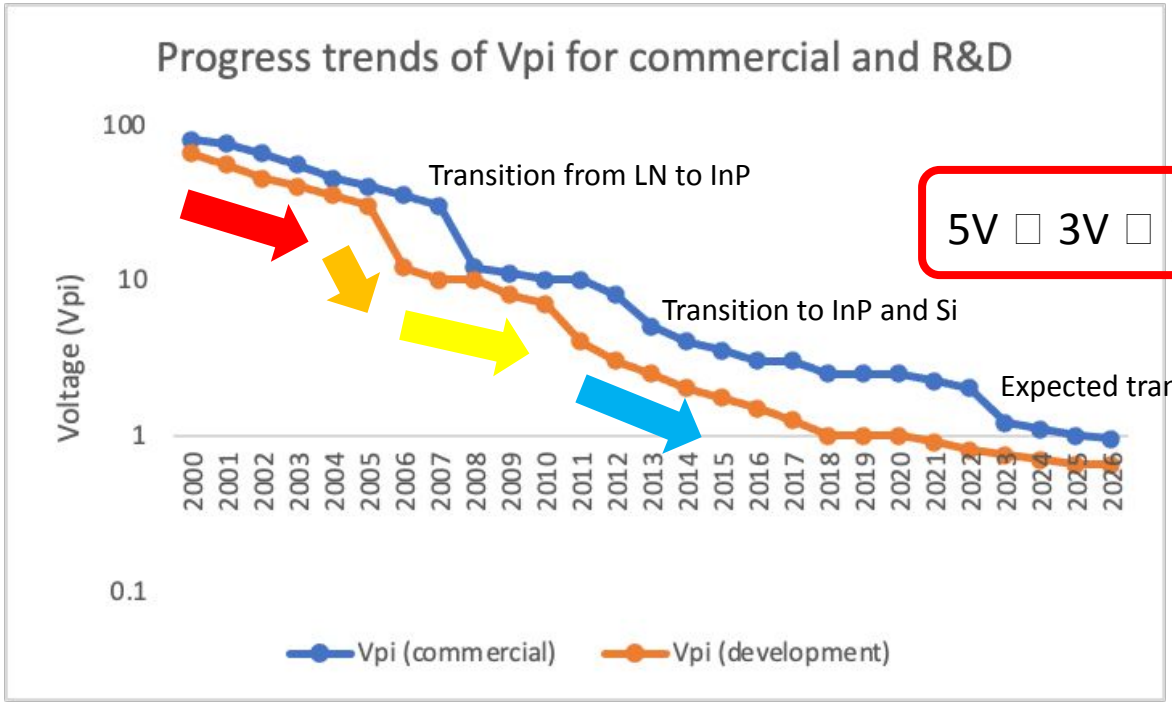
Source: Adapted from Arista (2022), Lightwave Logic (LWLG), OSFP MSA


Polymers are low power

Ultra-low voltage polymers save power…

LIGHTWAVE

- Low voltage polymers ----------Modulators can be driven directly from CMOS
- Lower voltage operation ----------Saves power (~2-3X at device level)
- Less IC chips/drivers on the line card --------Lowers power and cost (~5-10X at board level)



Key

- Power hungry
- High power
- Moderate power
- Low power

Commercial progress trails development progress ~5yrs

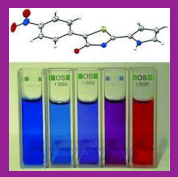
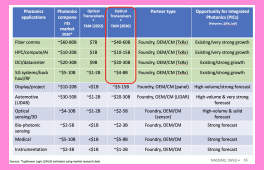
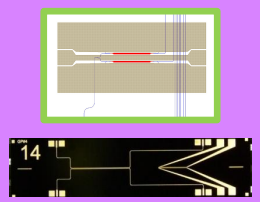
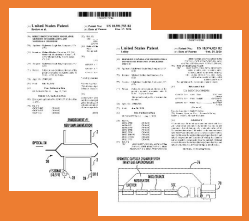
Transition to polymer is coming as low power issues become dominant

Source: Lightwave Logic (LWLG) research and estimates


Summary

Summary…

LICHTWAVE

Material Science	Standard fabrication & testing	High speed device design & packaging	Powerful patent portfolio	Huge $B markets
			UNITED STATES PATENT AND TRADEMARK OFFICE DEPARTMENT OF COMMERCE	
Selling components	Licensing polymer materials	Technology transfer (to foundries)	Solving key internet Achilles Heels	Volume scale with silicon foundries
			B/W Power	

Takeaways

LIGHTWAVE

- We have *unique* polymers…
- Our technology is *ultra*-fast and *ultra*-low power…
- We are positioned to have polymers become *ubiquitous*…
- Polymers are *foundry compatible…*

Investor Relations Contact

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Thank you!