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Faster by Design

Are electro-optic polymers two sides of one coin?

Michael Lebby, CEO

NASDAQ
LWLG

EPIC Technology Meeting: Microelectronics and photonics – two sides of one coin.
November 2023

Safe Harbor

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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.


Two sides of one coin...

Two sides of one coin…

- Much the same
- Cut from the same cloth
- Double-edged sword
- Two peas in a pod
- Adjacent
- Apples and oranges
- Two of a kind
- In the same league
- On equal footing
- Interchangeable
- Parallel
- Same same, but different
- Indistinguishable

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…different ways of looking at or dealing with the same situation…

Source: Lightwave Logic (LWLG), word selector, Wikiepedia (2023) Antoninianus-Tranquillina-Gordian III-s2539


Are the sides independent or symbiotic?

Microelectronics…

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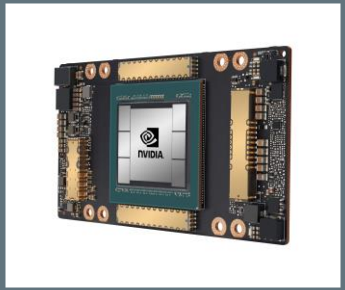
- Microelectronics is the manufacture (or microfabrication) of *very small electronic designs and components.*
- These devices are typically made from semiconductor materials in *silicon foundries*
- Many components are available in a microelectronic equivalent.
  - These include *transistors, capacitors, inductors, resistors, diodes* and, insulators and conductors etc.
- Unique wiring techniques such as *wire bonding, flip chip bumping* are also often used because of the *unusually small size of the components,* leads and pads.



…micro-digital integrated circuits for electronics…

Source: Lightwave Logic (LWLG), wikipedia (2023)

Photonics…

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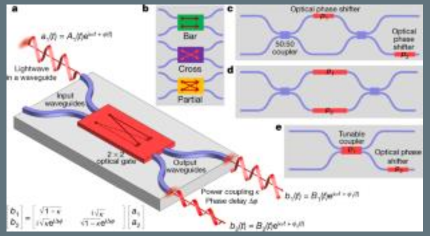
- A photonic integrated circuit (*PIC*) is a microchip containing *two or more photonic components* which form a functioning circuit.

- PIC technology detects, generates, transports, and processes light. *PICs utilize photons* (or particles of light)

- A PIC provides functions for *information signals* imposed on optical wavelengths typically in the visible spectrum or near infrared (850–1650 nm).



…Photonics integrated circuit (PIC) 2 or more components…

Source: Lightwave Logic (LWLG), Nature (2023)


Market Dynamics…

New frontiers in electronics and photonics

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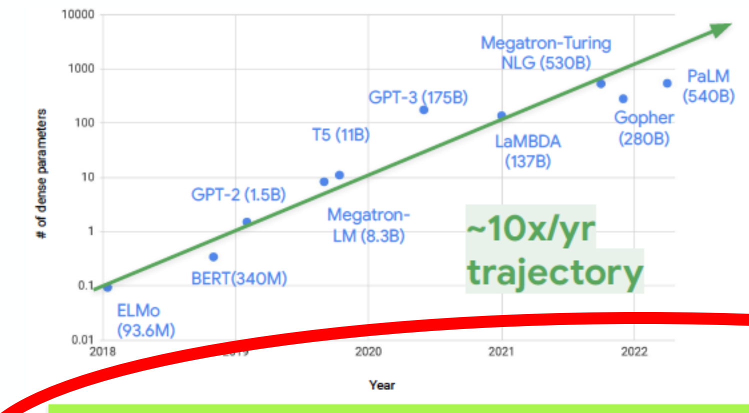
Generative AI Changes Everything



ChatGPT 4.0 Model Size > 1T Parameters

Large Language Model sizes have been increasing 10X per year

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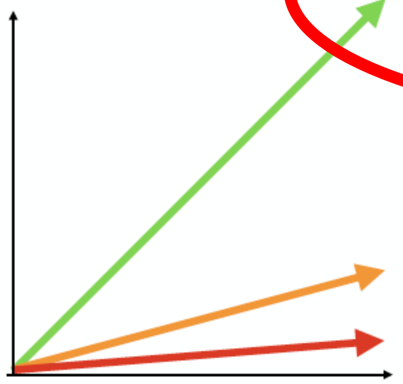
A 10X Gap



LLM Sizes Growing 100X / 2 Years

AI Cluster Performance 10X / 2 Years

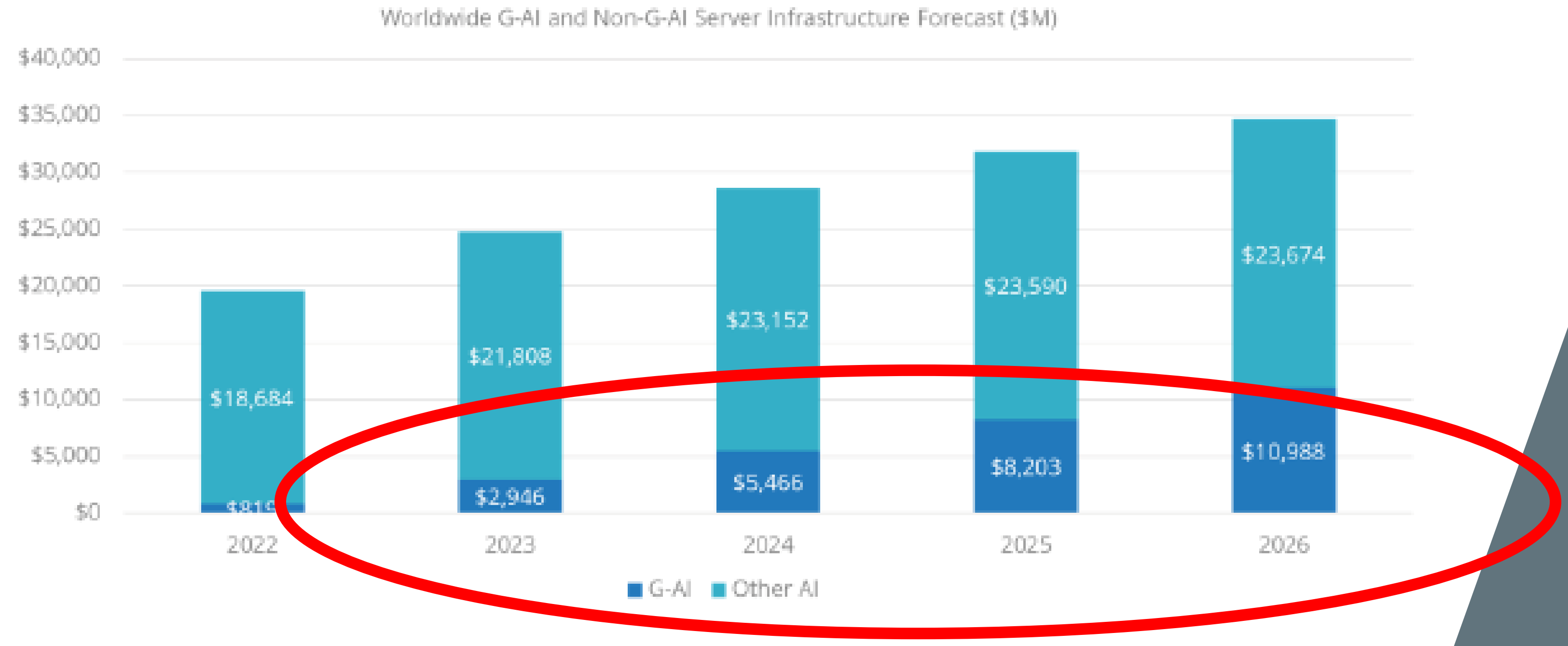
Moore's Law 2X / 2 Years

To accelerate AI we need "More than Moore"

G-AI is driving new frontiers in both electronics and photonics

Source: Lightwave Logic (LWLG), Arista (2023)

General-AI market growing quickly



Source: IDC

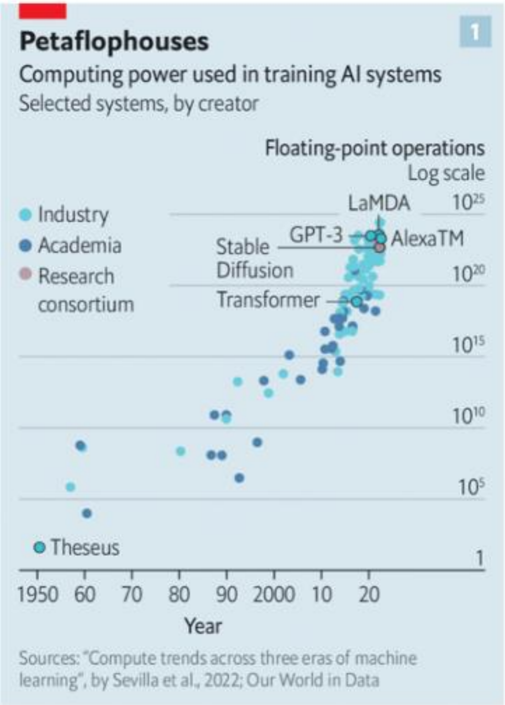
Estimated CAGR for "AI-Transceivers" alone is 44%

The driver for upgrading transceiver optics in the datacenter and optical network…

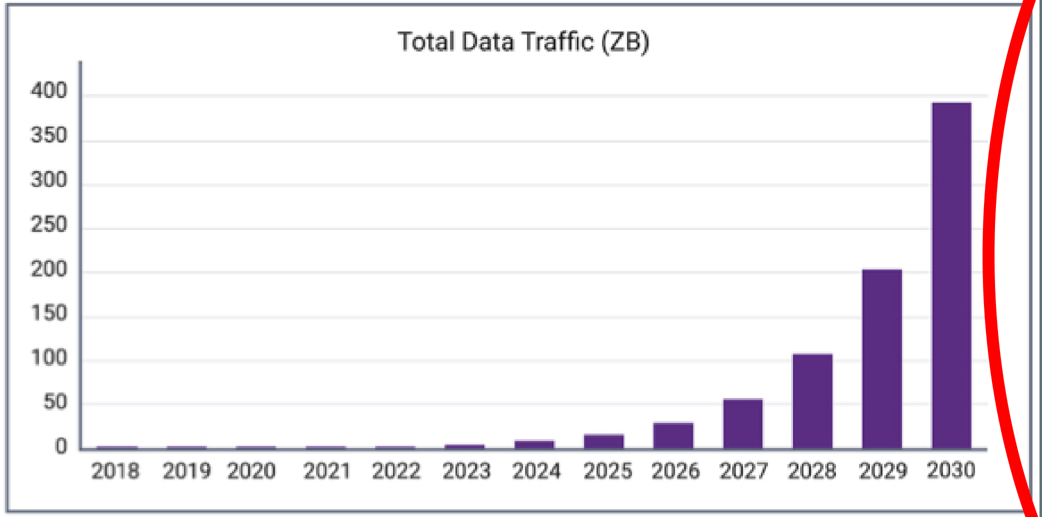
~20% of G-AI data center capex is expected to be 800G transceivers ($3B in 2026)

Source: Lightwave Logic (LWLG), IDC

The importance of photonics in communications



The Economist



The growth driver of "communication" is datacom…

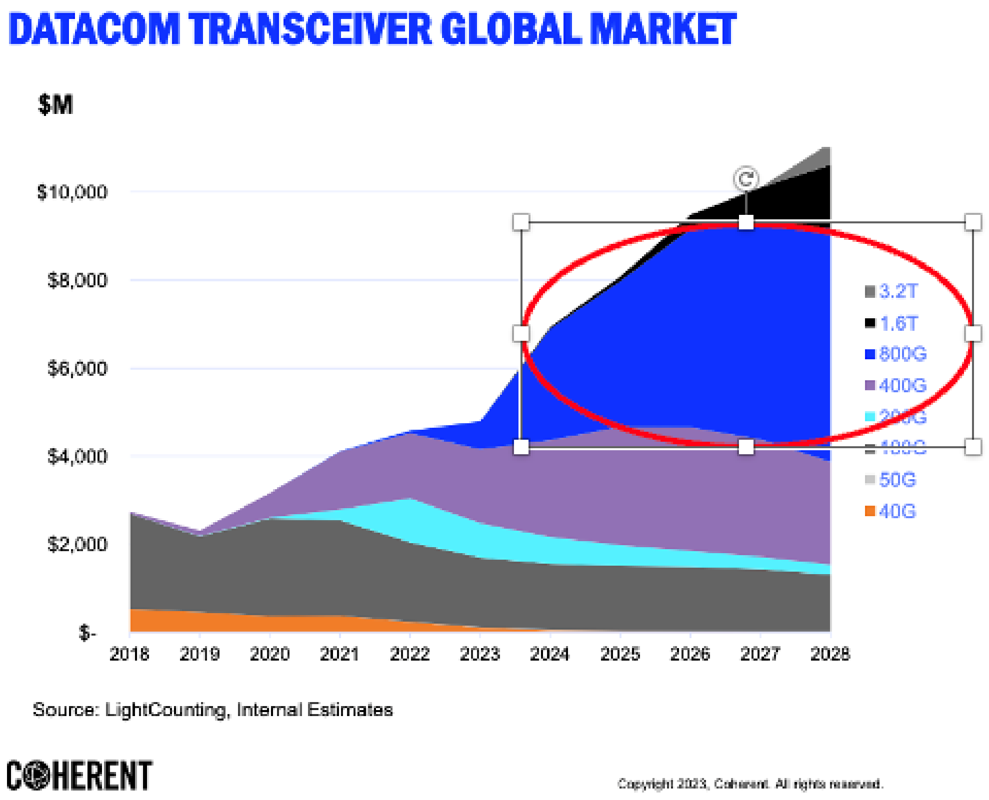
…The growth driver of datacom is largely Generative AI

The twin enablers of G-AI are photonics and GPUs

Datacom → Generative AI → Electronics (GPU) and photonics

Source: Lightwave Logic (LWLG), Economist, Cisco

The importance of photonics in communications



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800Gbps and 1600 Gbps transceiver modules

Need to upgrade in speed, and lower power consumption

Source: Lightwave Logic (LWLG), Coherent, Lightcounting (2023)

Optics is No Longer A "Minor" Contributor to Datacenter G-AI Power Issues

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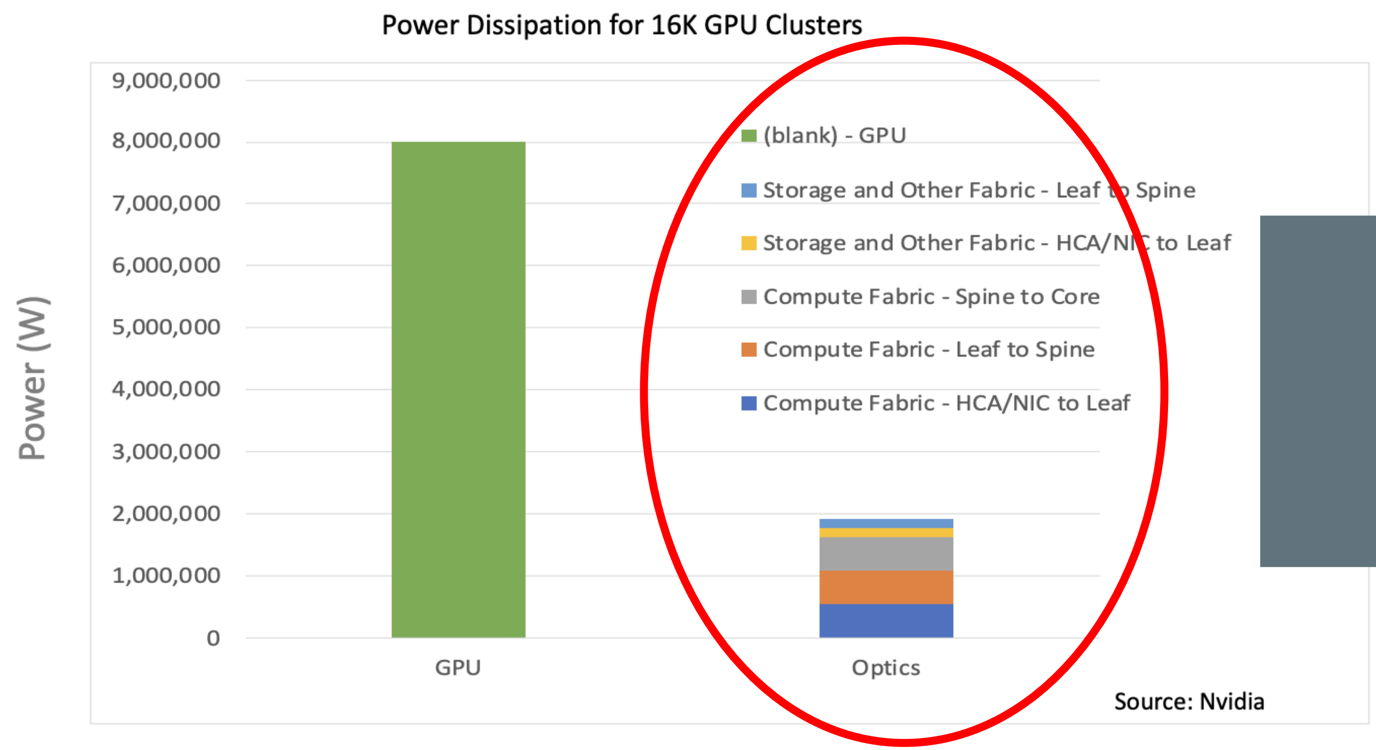


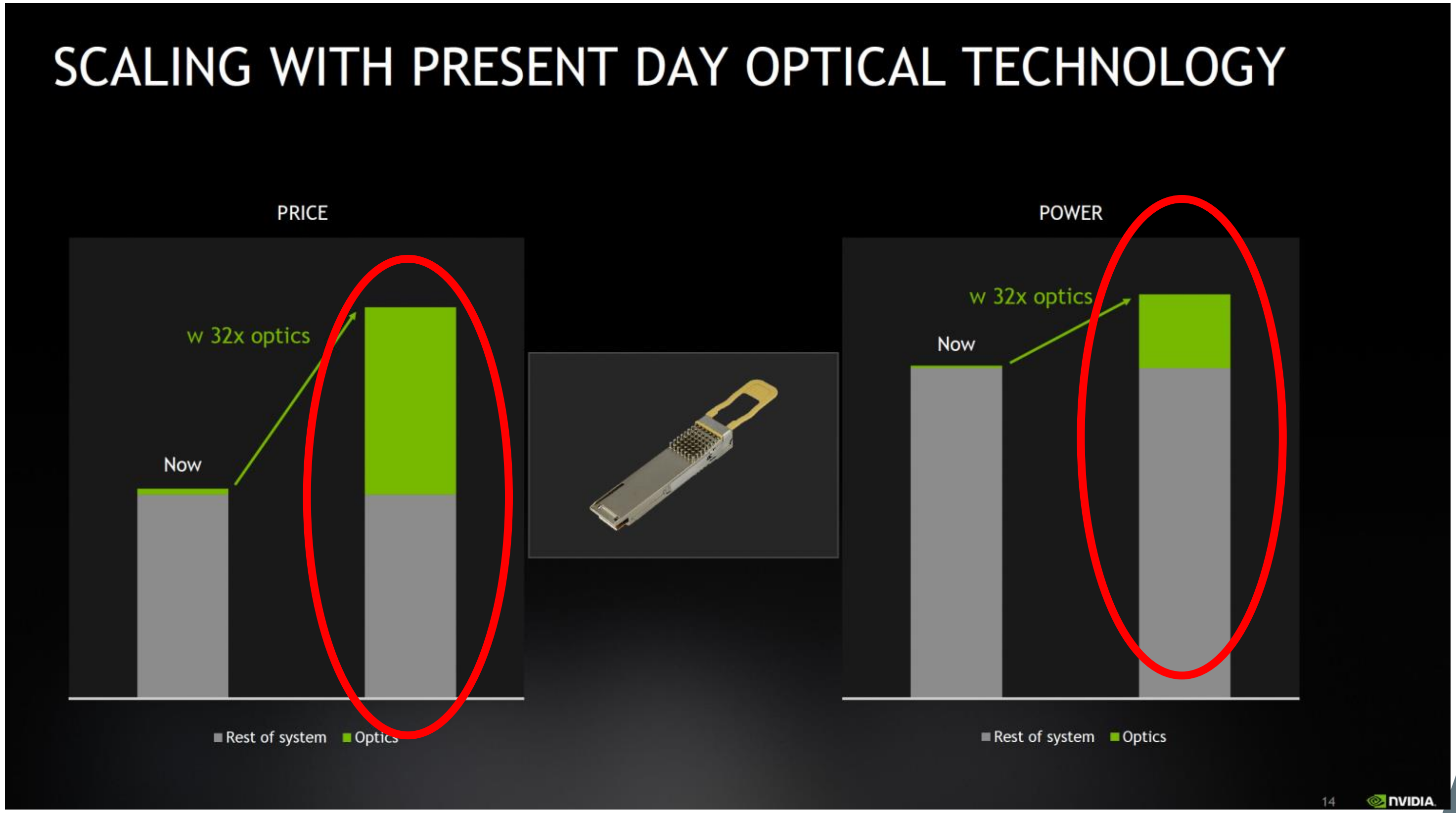
Power dissipation for AI cluster optics showing optical network power dissipation share increasing…

Large language models requires large GPU clusters (ChatGPT 4 training requires ~25,000 GPUs)

For 16,000 GPU clusters, optics consume ~2MW (equivalent to 4000 GPUs) – source: Nvidia, CIOE, Song, 2023)

Source: Silicon Photonics Solutions for AI/Data Center Applications Rang-Chen Yu, Dong Pan SiFotonics Technologies, ECOC 2023

General-AI market growing quickly



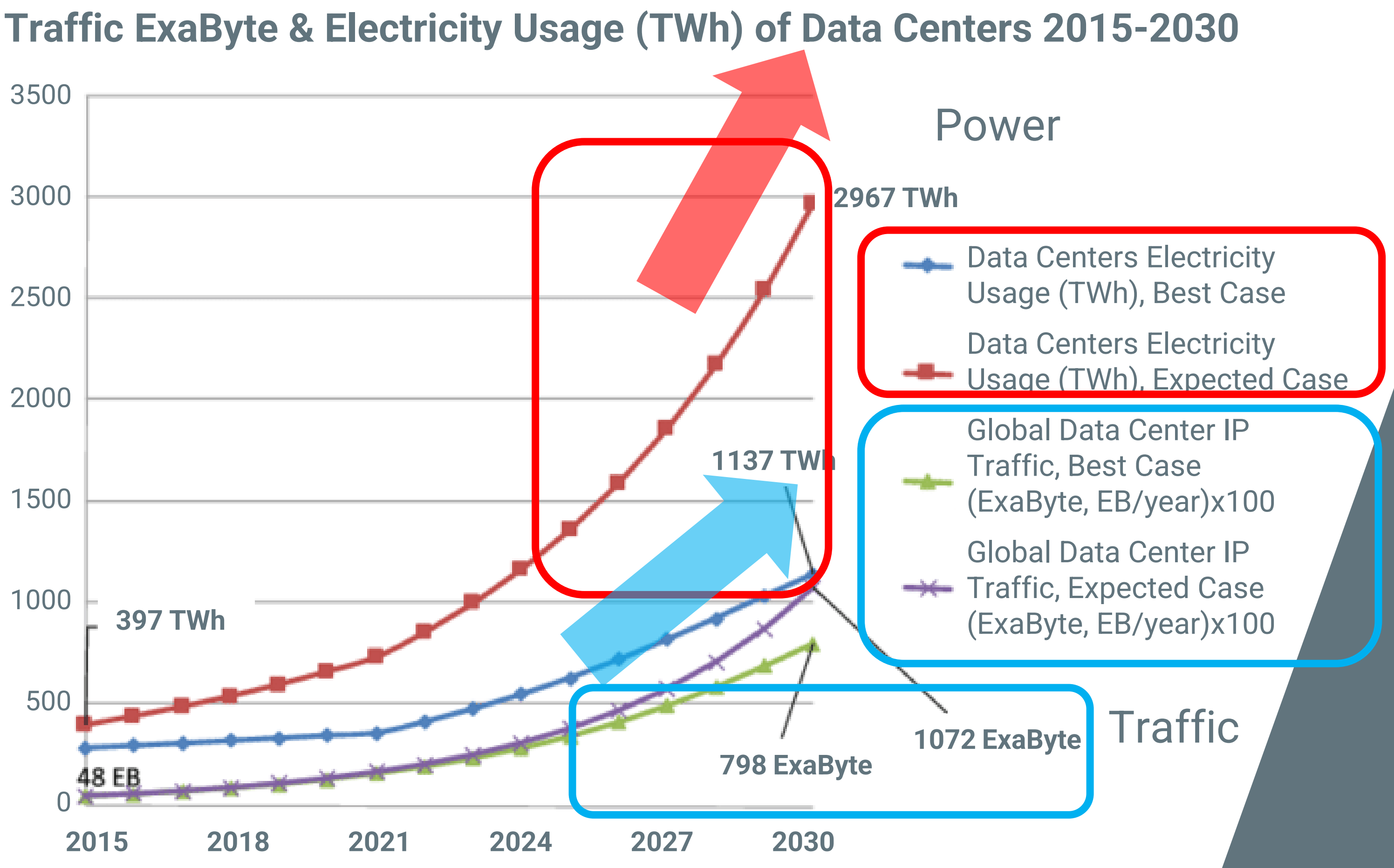
With faster (32x) optics - it becomes a huge effect on price and power

Datacenter photonics needs to improve quickly….

Source: Lightwave Logic (LWLG), Nvidia

The Achilles Heel

Existing solutions require excessive amounts of power to scale



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Data center power use is growing exponentially with increased traffic levels - *the Achilles Heel* and a major challenge for data centers and service providers

Source: Publication: Walnum, HJ et al


How can photonics help?

Role of photonics as part of the solution

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Key Requirements for Optics at AI Scale

Reliability

Need two orders of improvement to single-digit FITS per Terabit

Power Efficiency

Saving 10 pJ/Bit at 2.5 Exabit/sec equals 25 Megawatts

Cost per Bit

Need to drive from double-digit to single cents/Gigabit.

Progress is being made on all of these fronts,
but progress needs to be accelerated

Arista wish…

ARISTA

How to Reduce Optics Power

1. **Use Linear Drive Interface**
   Eliminates DSP/CDR power and cost
2. **Use lower power modulators**
   Lower drive voltage, lower insertion losses
3. **Use higher efficiency lasers with better coupling**
   Laser efficiency makes a major difference in overall power

In combination these reduce optics power from
15 pJ/Bit to 5 pJ/Bit, a reduction of 10 pJ/Bit

Arista wish…

Both electronics and photonics needs to improve…
…especially modulators

Source: Lightwave Logic (LWLG), Arista

Modulators will be part of the solution

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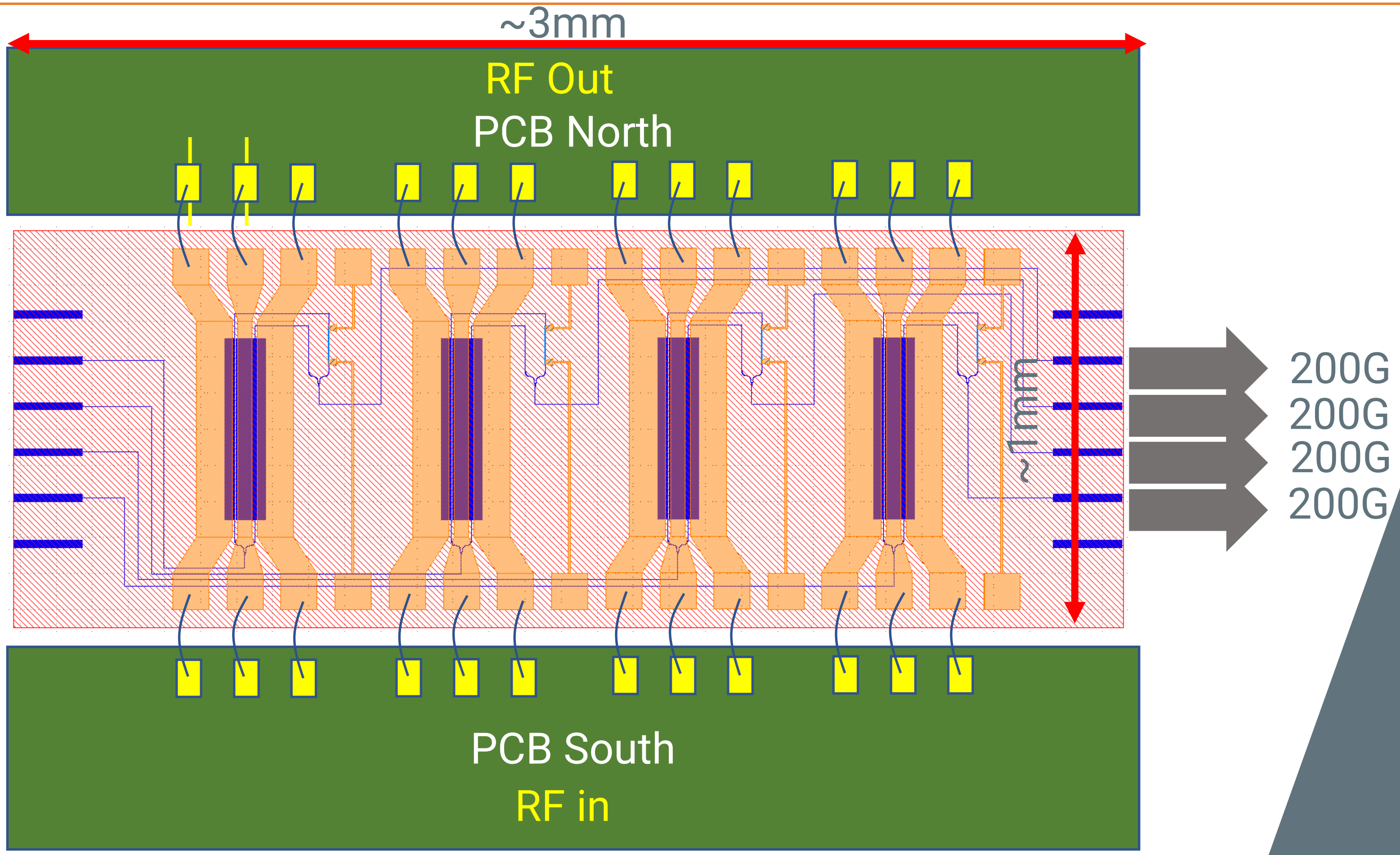

In development → 4 channel polymer PIC chip as part of our P^2IC platform

Potential for 300G and even 400G per lane*

- Optical 4 channel Polymer PIC layout with Mach Zehnder Interferometers (MZI) arrays
- Fiber array to be connected on both East and West side using Edge couplers
- Electrical CPW transmission length ~1mm

*Using EO S21 3dB bandwidths in excess of 150GHz, with the potential for >250GHz

Source: Lightwave Logic (LWLG)

Packaging will be part of the solution

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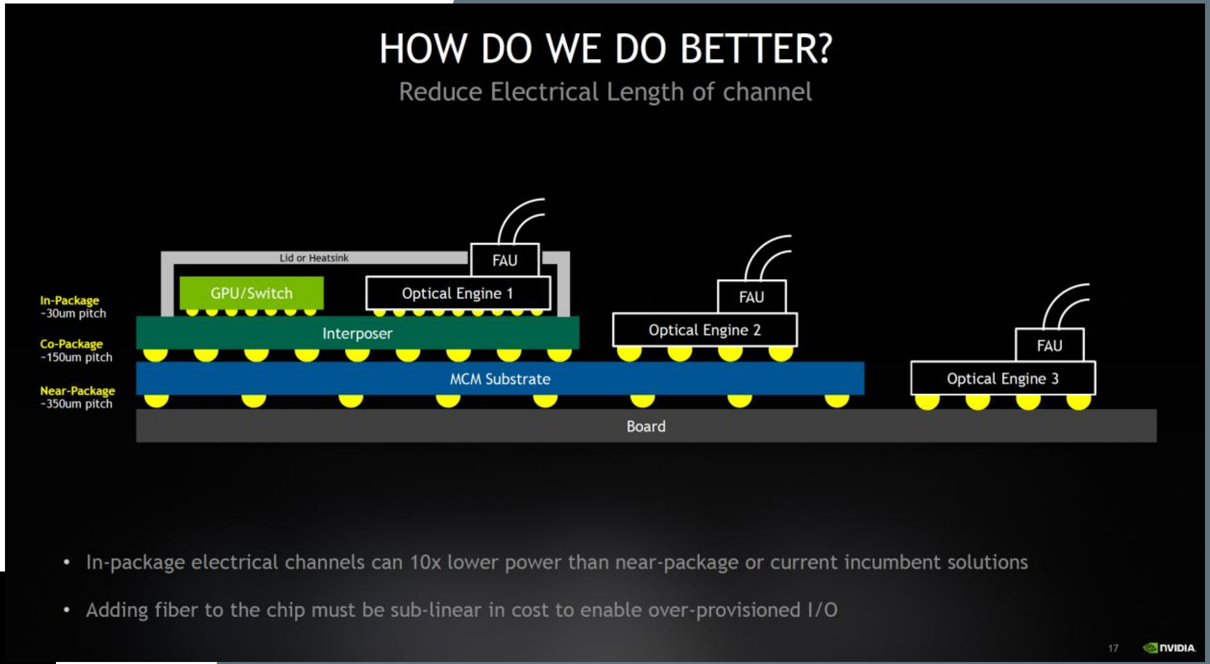

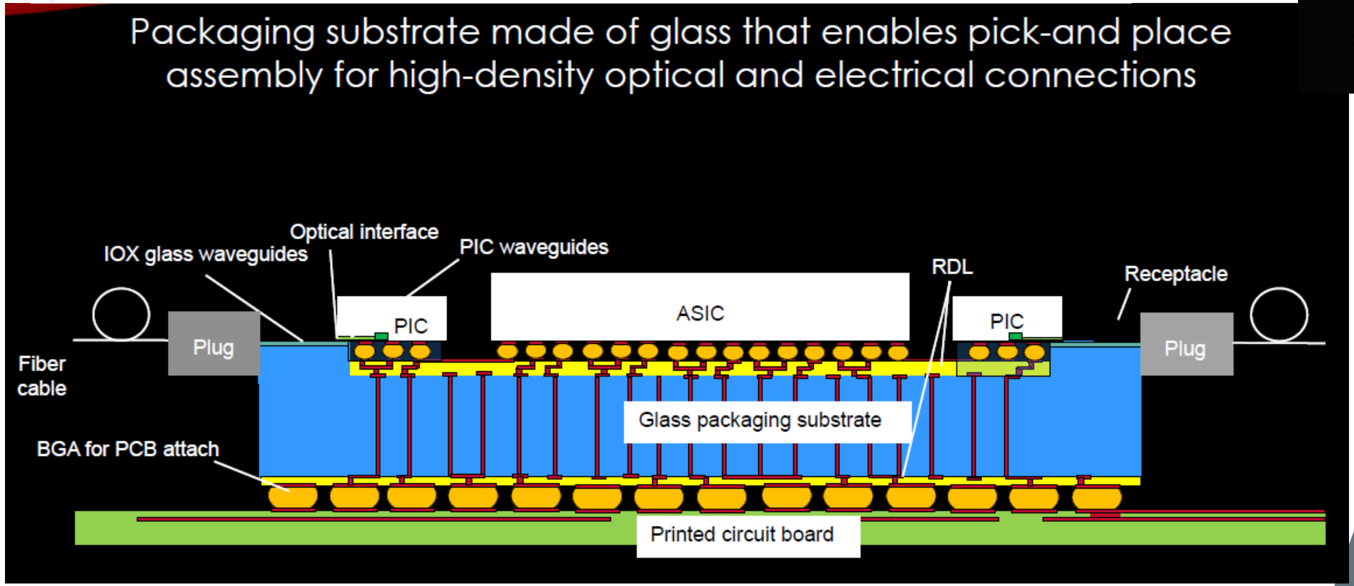

Packaging is becoming more complex…trend to chip-scale solutions

Source: Lightwave Logic (LWLG), Broadcom (2023), Corning, Nvidia

Foundries will be part of the solution

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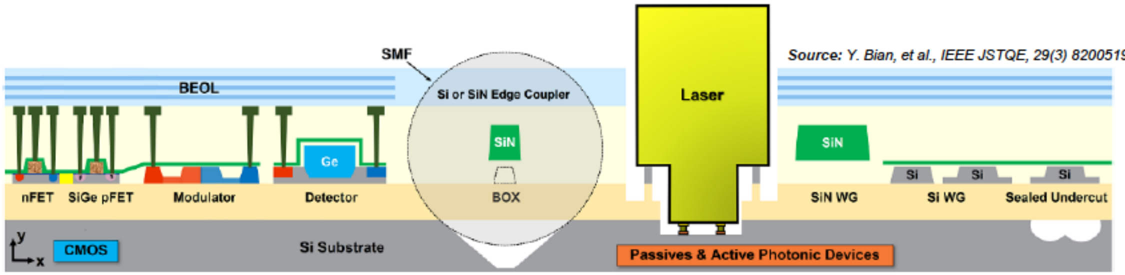
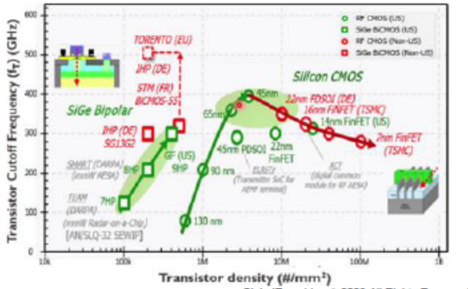
GF Fotonix™: Monolithic Silicon Photonics



Source: Y. Bian, et al., IEEE JSTQE, 29(3) 8200519 (2023)

- **Monolithic** integration of Photonic Devices with a 45nm class RFCMOS
- **300mm** process leveraging immersion lithography
- **Advanced immersion lithography** SOI WGs and photonic OPC
- **Features**:
  - Comprehensive photonic passive device library
  - High performance photonic active devices
  - High efficiency sealed undercut (airgap) thermal heaters
  - Micro-ring modulators and dWDM ring filters
  - Freeform design enabled: accepts custom curve-linear GDS
- **Packaging**: V-groove fiber attach, laser cavity, Cu pillar & TSV
- **Test**: Wafer level state-of-art optical / electrical test capability

https://www.darpa.mil/attachments/T-MUSIC_Proposers%20Day_Jan30.pdf



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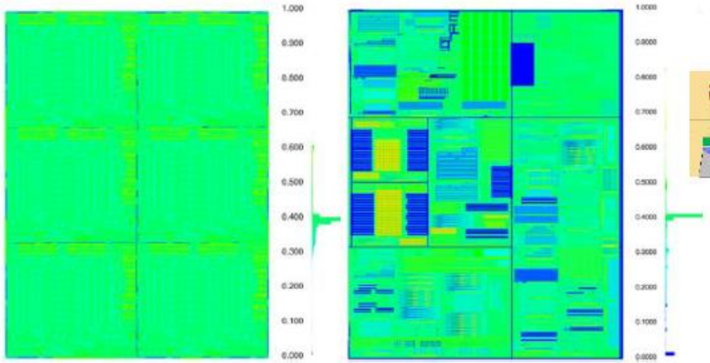
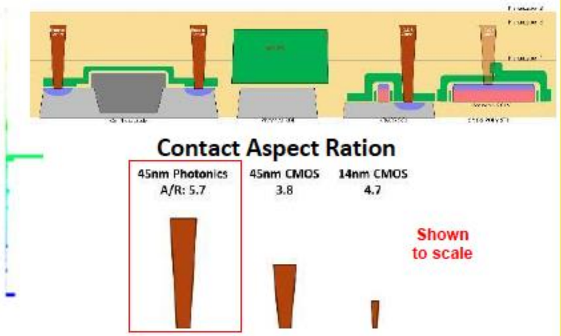
GF Fotonix™: Process Window



TYPICAL M1 (UNIFORM)
CMOS PATTERN DENSITY

TYPICAL M1 ("KEEP AWAY")
SiPH PATTERN DENSITY

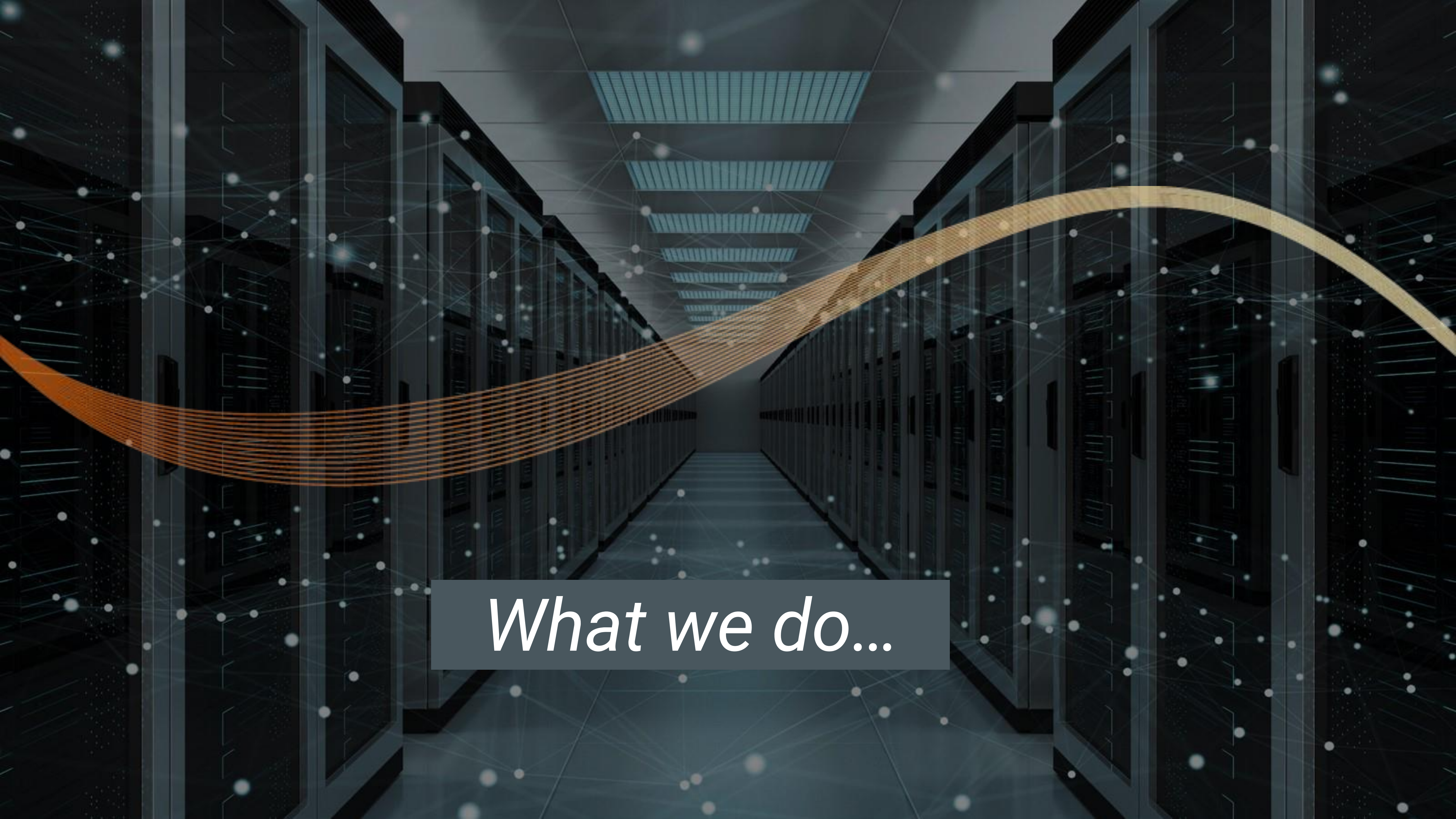


Process windows are reduced due to keep away zones & high aspect ratios

 10

Creating PDKs for silicon photonics (that include hybrid technologies)

Source: Lightwave Logic (LWLG), Global Foundries



What we do…

Perkinamine® Electro-Optic polymers

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Our polymers are world-class and proven by third parties

Electro-optic polymers can be used to fabricate optical modulators which enable:

- High material-level thermal and photostability
- Long-term storage and operational durability
- >3x faster modulation than existing products
- ~10x lower power than existing products

EO polymers → Fast, stable, reliable, low power consumption, and very small in size

Source: Lightwave Logic (LWLG)

3rd Party Use of Perkinamine®

- **EO polymer** used in different device designs
- Silicon slot, plasmonic slot, plasmonic ring resonator
- All produced **world class** results*
- Presentations at industry conferences globally

Sources*: Nature Photonics: Resonant plasmonic micro-racetrack modulators with high bandwidth and high temperature tolerance (ETH Zurich, Polariton and LWLG EO polymer material)

Sources*: KIT, SilOriX, EU Horizon 2020, ETH Zurich, Polariton, CAU University Kiel (post deadline paper published at ECOC2022 using LWLG EO polymers)

Polymer modulator opportunities

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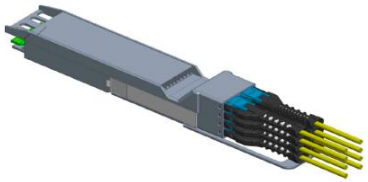
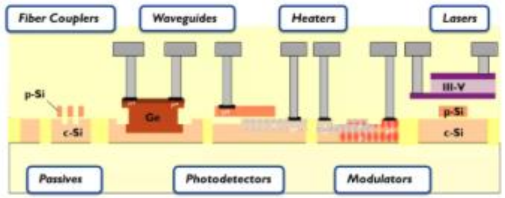
Electro-optic polymer modulators for transceivers suppliers

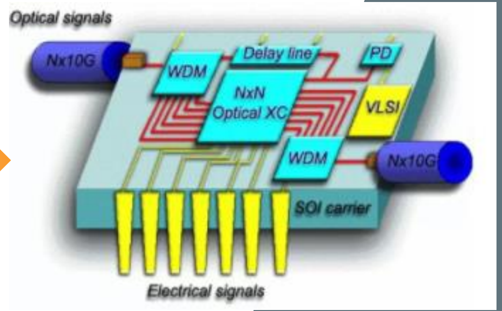


Electro-optic polymer modulators for Silicon Photonic platforms



Source: ePIX Fab

Electro-optic polymer modulators for "Other"
platforms including optical/quantum computing, HPC, and RF applications



EO polymers enable higher performance data communications

Electro-optic polymer engines for fiber optic communications

Source: Ethernet Alliance, OSFP MSA, https://www.researchgate.net/figure/Schematic-of-an-on-chip-optical-network-with-various-components-illustrated-including_fig2_239929876, ePIXfab, corning


Reliability and stability…

Optimized for reliability & stability

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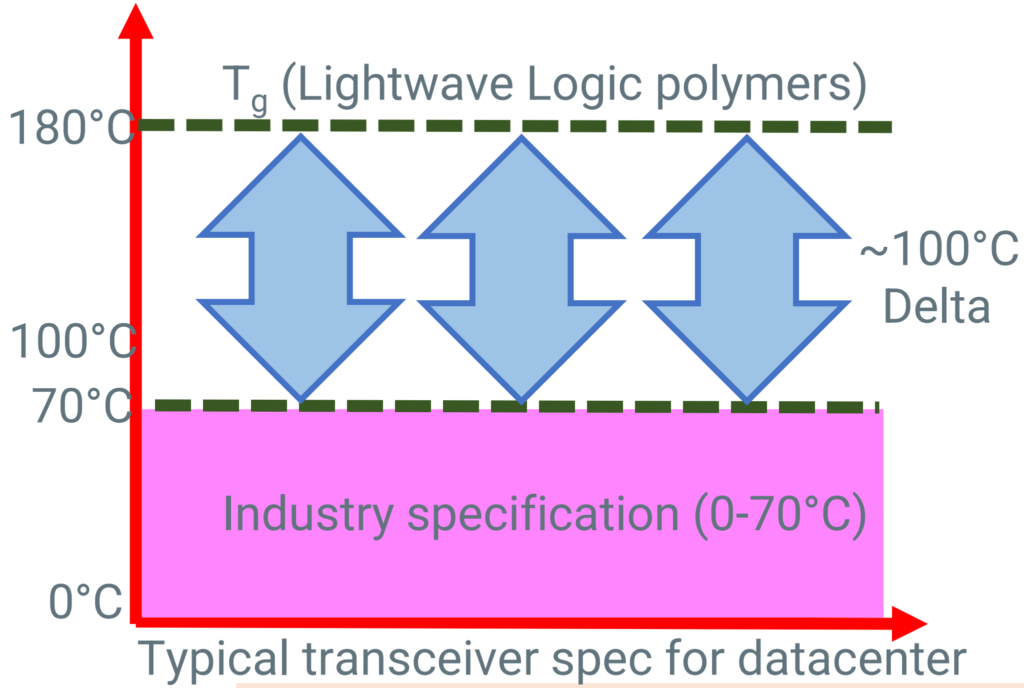
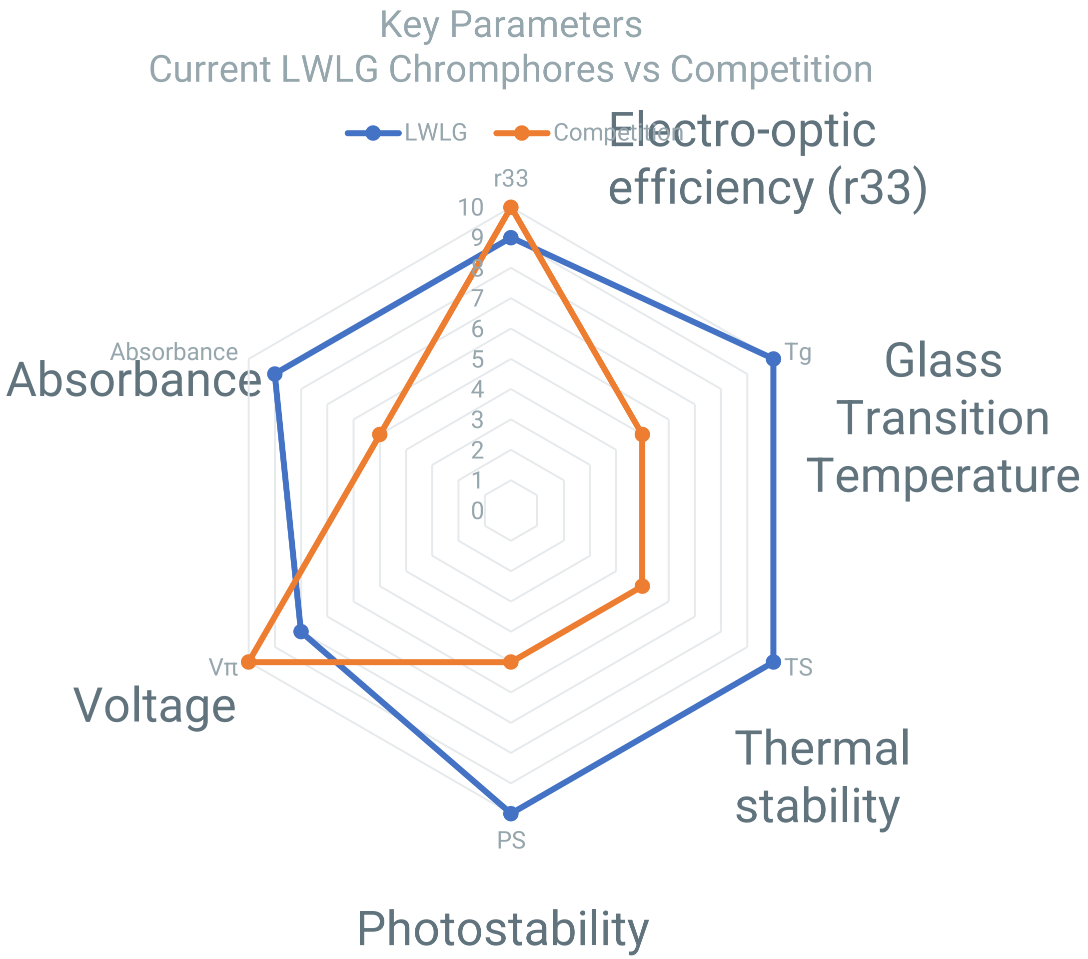
- **World class chromophore design**
  - Very high glass transition temperature (T_g)
  - ~100°C delta between industry spec and T_g
  - Eliminates need for cross-linking
  - Protects material from de-poling (occurs when T_g is close to industry specification high limit)





Electro-optic material designed for reliability, stability, and overall operational performance

NB: These are *qualitative* analyses only: i.e. on a scale of 1-10, how "good" is the material in terms of the particular parameter.

*Source: Lightwave Logic (LWLG), *best estimates of public data*

How important is glass transition temperature (T_g)?

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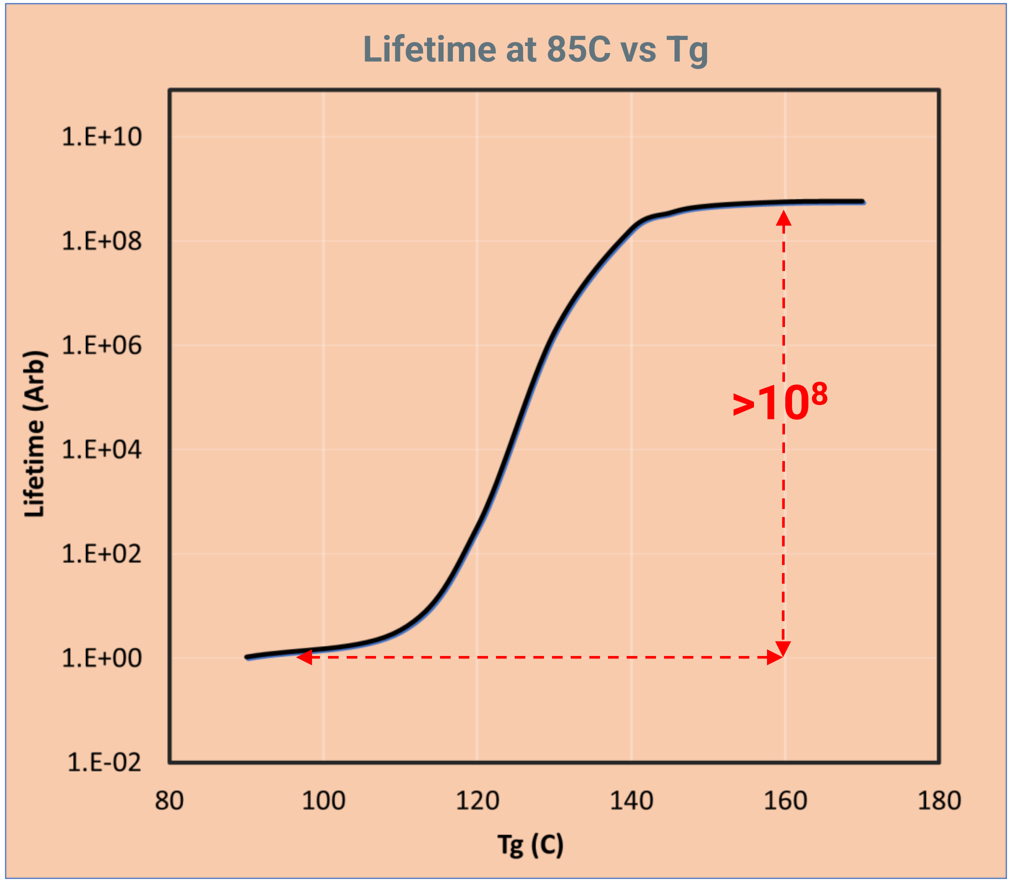

The thermal lifetime of an EO-polymer material at 85C will increase with increasing Tg

The lifetime at 85°C for a polymer with **T_g =160°C is >10^8 times greater than** the lifetime for a polymer with **T_g= 90°C**

Increasing Tg → means much higher lifetime in electro-optic materials

Using the widely quoted Lindsay's time constant formula which is found in ***Polymer 48 (2007) 6605-6616***

$$\ln(\tau/\tau_P) = E_R\left(1 + \tanh\left[(T_c - T)/D\right]\right)/2RT + E_p/RT$$

Source: *Lightwave Logic (LWLG), Lindsay et al (2007)*

How have EO polymers improved over the last 6 years?

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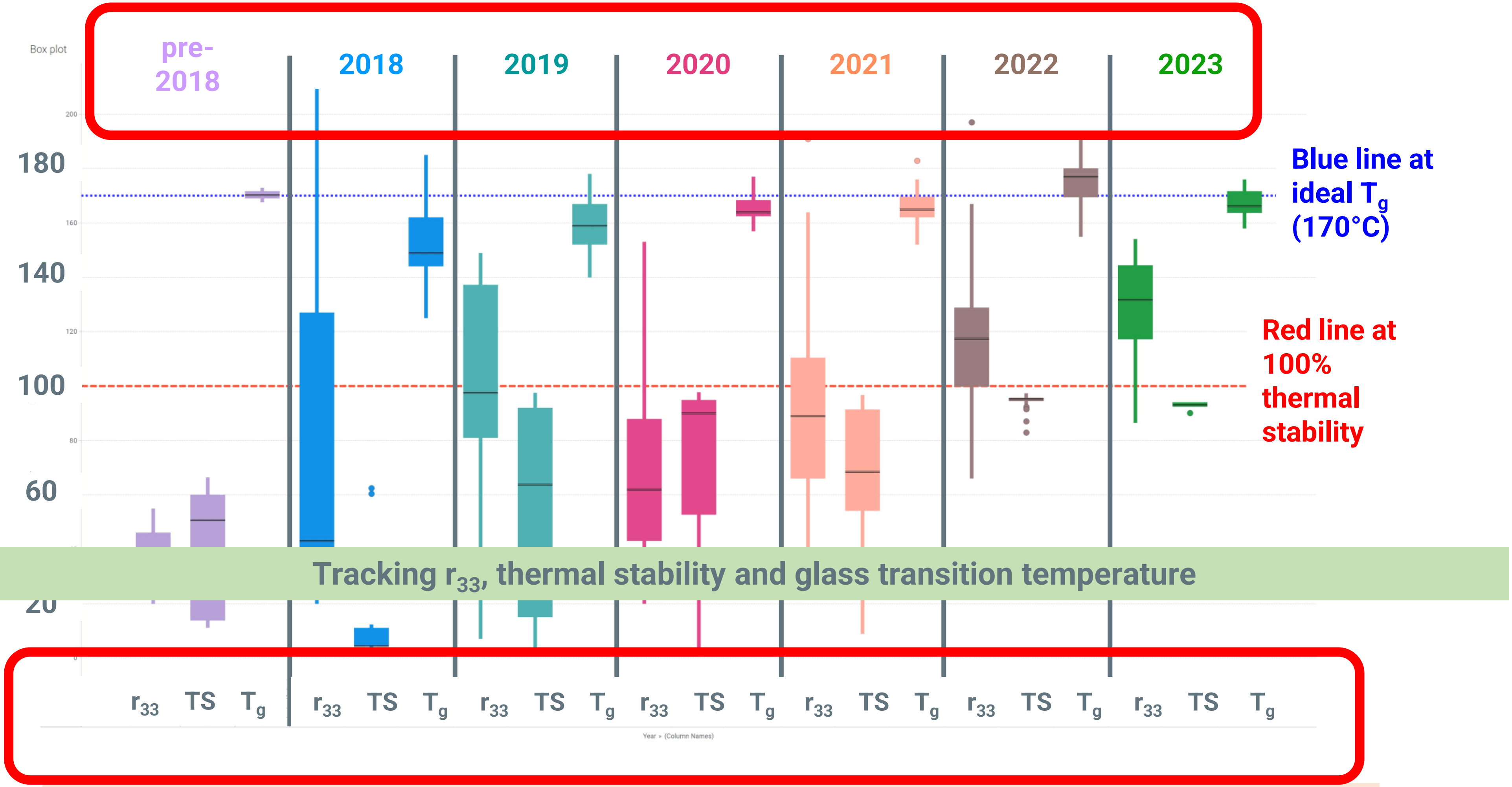
Box plot of Perkinamine®



Tracking r_{33}, thermal stability and glass transition temperature

A box plot or boxplot is a method for graphically demonstrating the locality, spread and skewness groups of numerical data through their quartiles

*Source: Lightwave Logic (LWLG), *best estimates;*

Tracking r_{33} improvements

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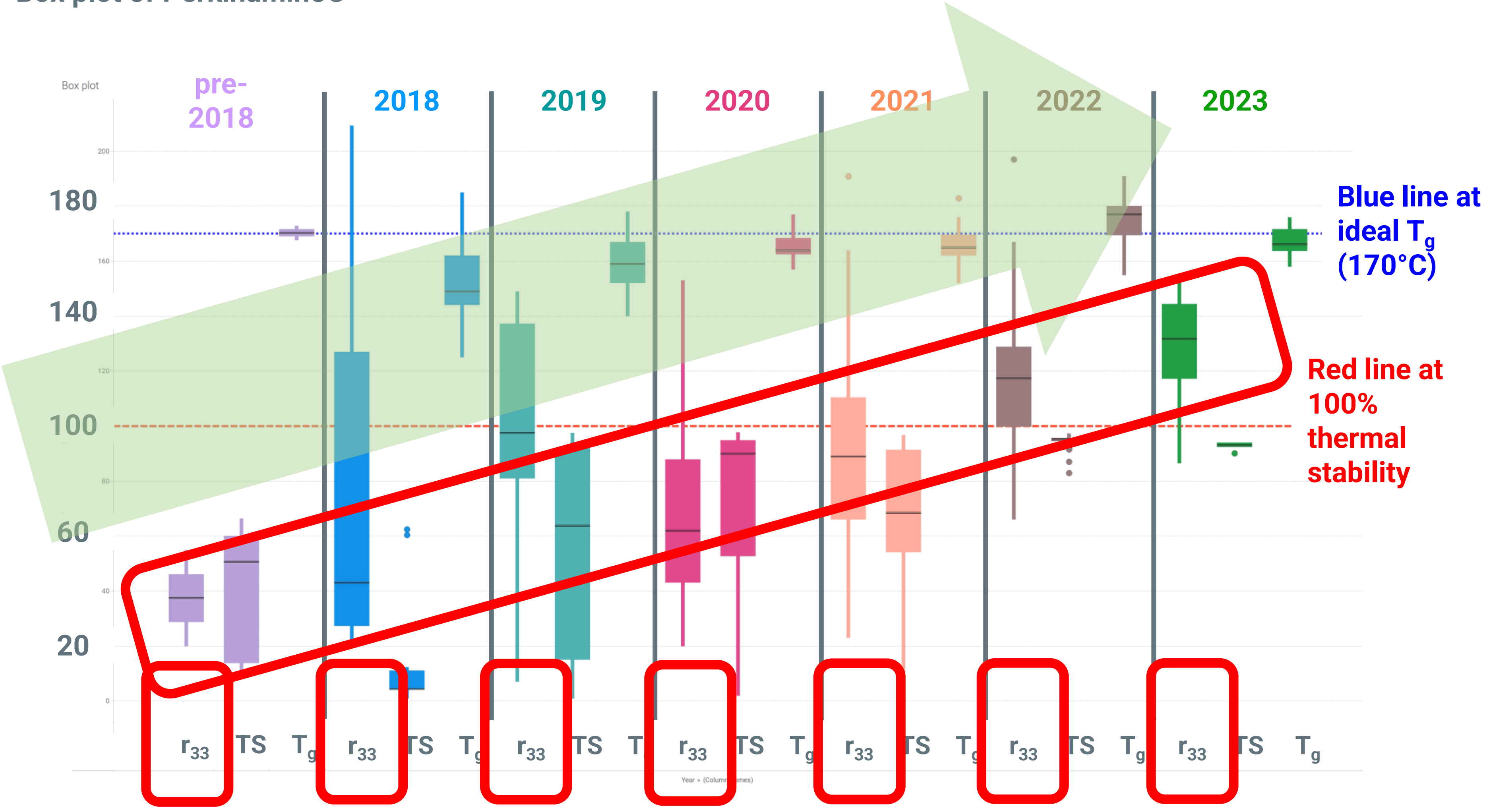
Box plot of Perkinamine®



r_{33} improved 5X over past 6 years; and now very stable in testing

*Source: Lightwave Logic (LWLG), *best estimates*

Tracking TS (Thermal Stability) improvements

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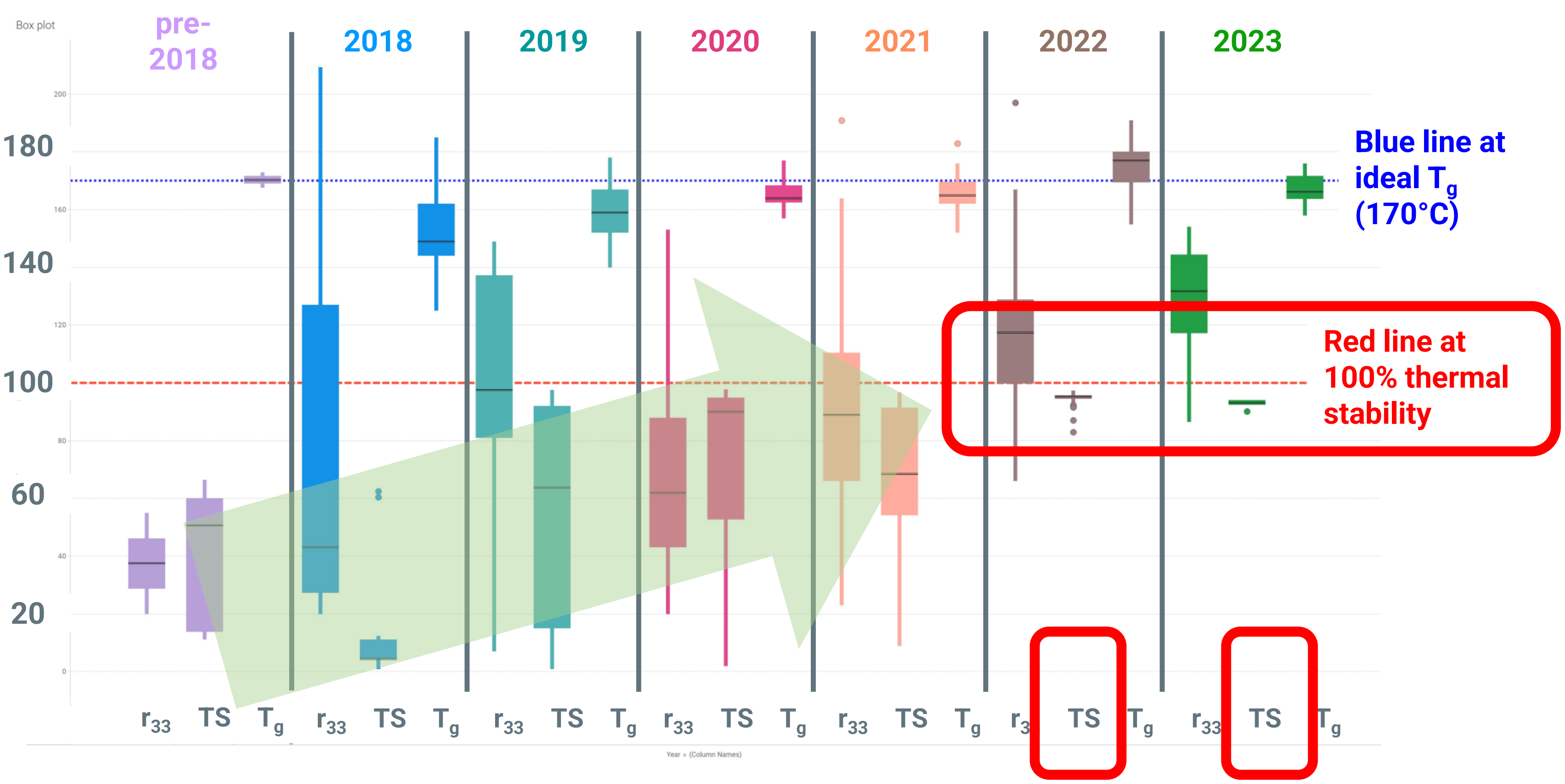
Box plot of Perkinamine®

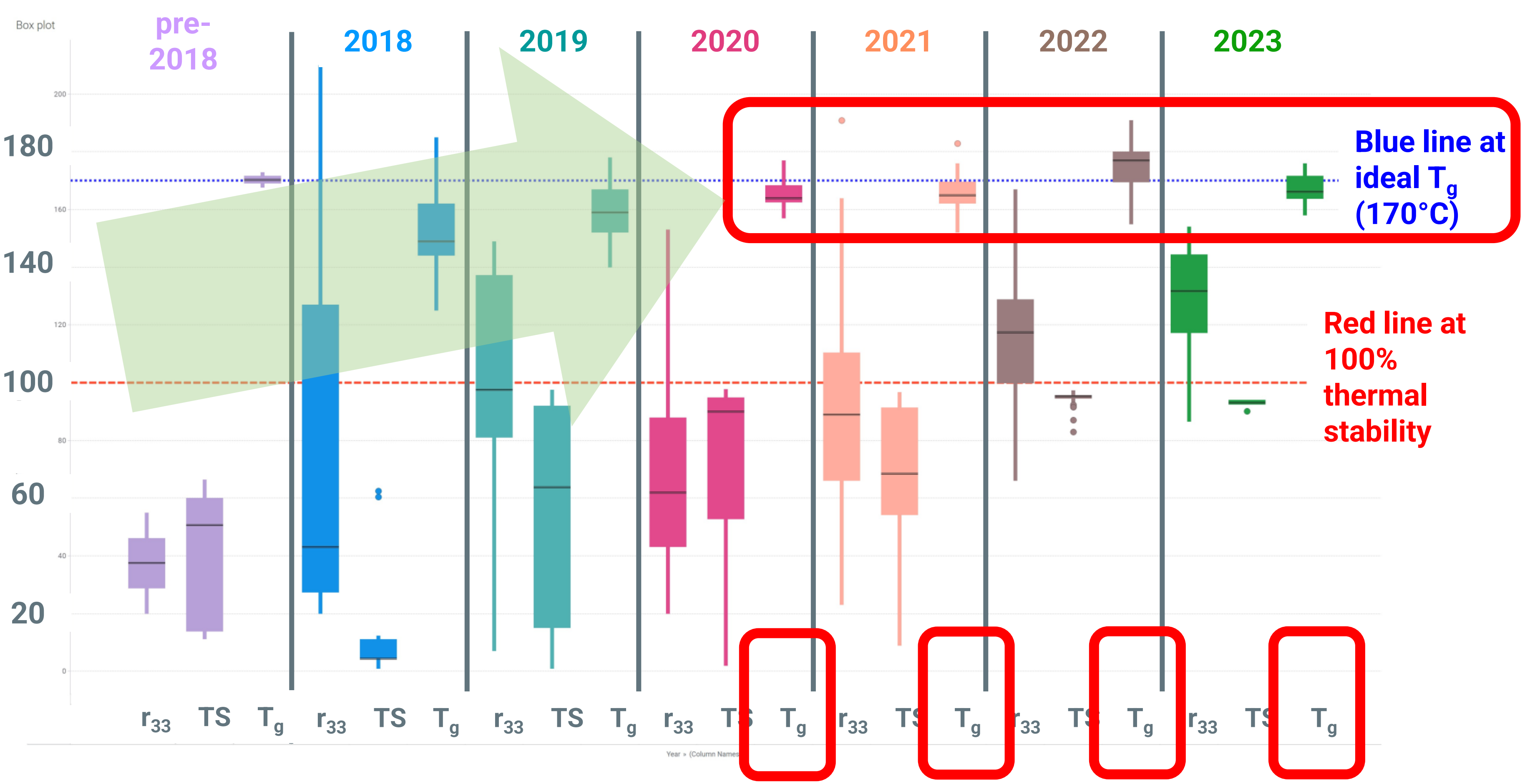


Super performance of material thermal stability in last 2 years (approaching 100%)

*Source: Lightwave Logic (LWLG), *best estimates*

Tracking glass transition temperature (T_g)

Box plot of Perkinamine®



Tight control of materials with extremely high T_g at 170C

Source: Lightwave Logic (LWLG), *best estimates

Photostability vs Voltage and Insertion Loss

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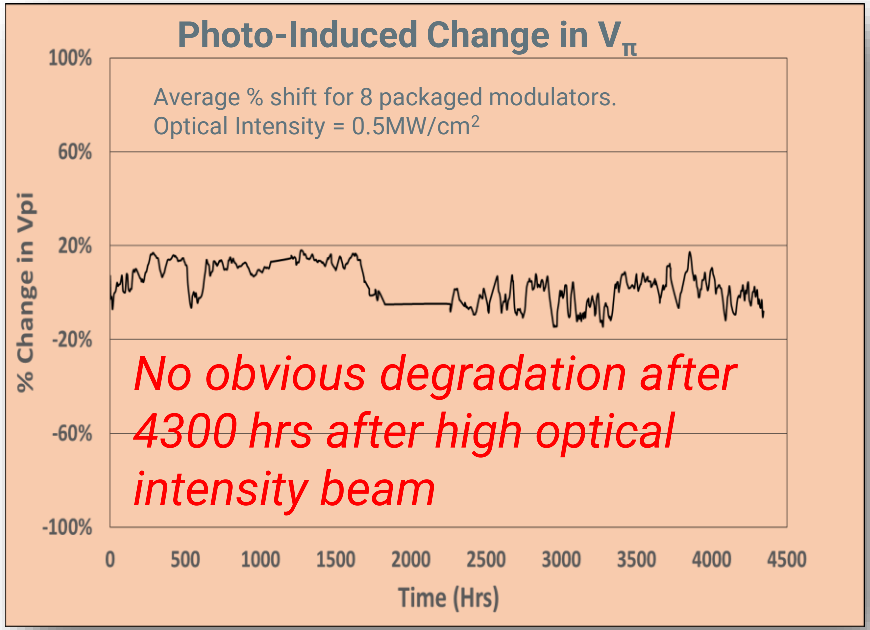

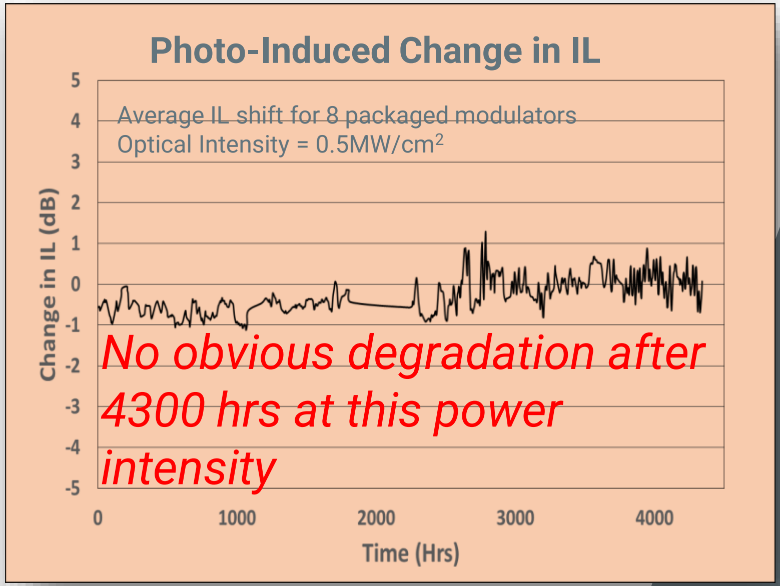

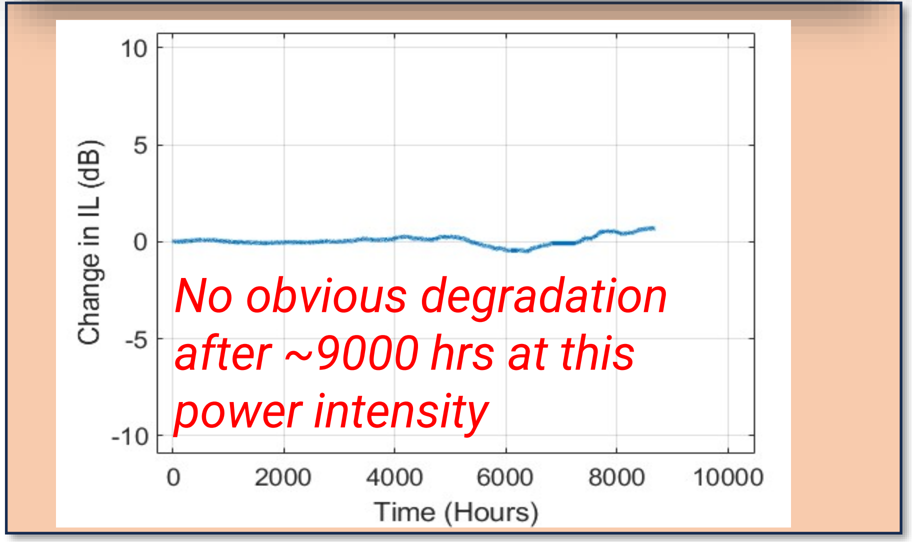

Long and short-term photostability does not seem to be an issue with LWLG electro-optic chromophores

Source: Lightwave Logic (LWLG)

Device Thermal Stability (TS) against change in voltage

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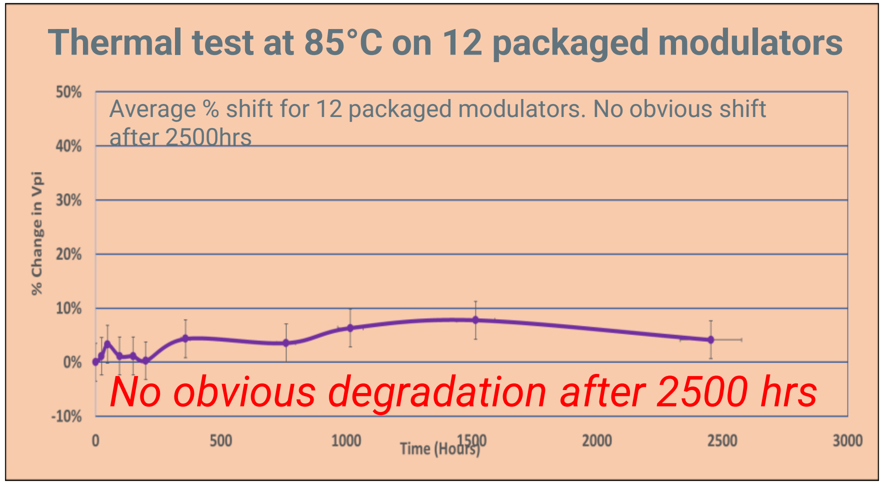

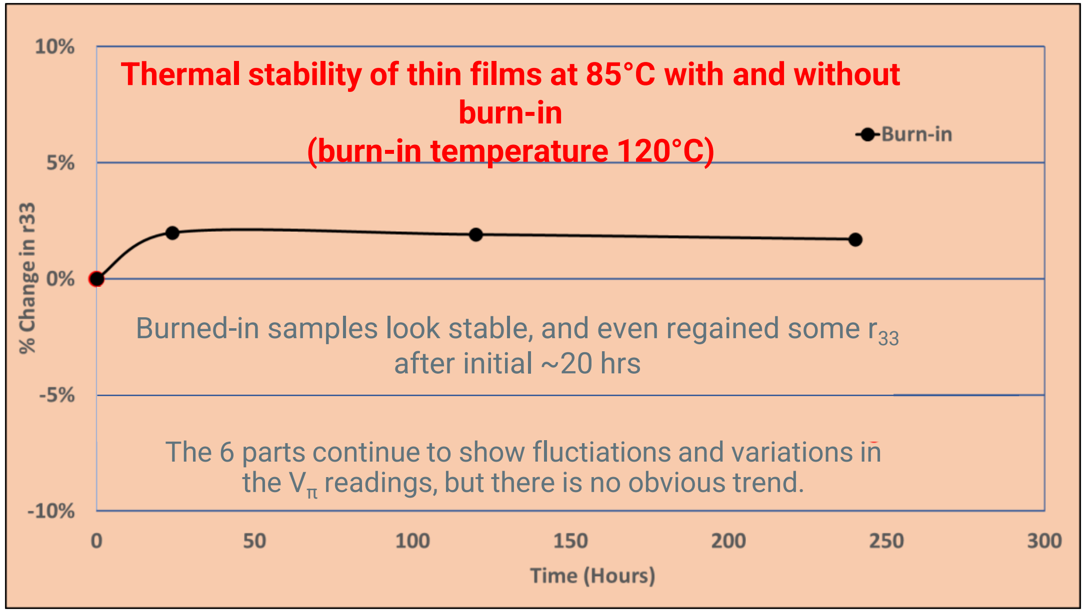

Thermal stability does not seem to be an issue with LWLG packaged modulators or burn-in against change in r_{33}

Source: Lightwave Logic (LWLG)

Polymers (organics) on system roadmap

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EOM Technology Comparison

Technology	Integration Capability	Bandwidth	Vpi (1)	Insertion Loss (2)	Reliability	HVM (3)
Silicon Photonics	Excellent	Good	High	High	Proven	Now
III-V	Low	Higher	Lower	Low	Proven	Now
TFLN	Low	Very High	Lower	Low	Proven	2024 (E)
BTO	New Process	Very High	Low	Low	Proven	2025 (E)
Organic	New Process	Very High	Lowest	Low	To be Proven	2026 (E)

(1) Tx Drive power is CV^2 ·f-dominated
(2) Lower insertion loss reduces laser power
(3) HVM = High volume manufacturing

Lower Vpi Drive Voltage results in significant power reduction

Our focus is on:

1) lifetime & reliability

2) TTM (time to market)

Source: Lightwave Logic (LWLG), Arista (2022)


Trying electro-optic polymers...

Implementing a new technology platform…

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Licensing model provides inherent scalability

Technology

Chromophore & Polymer Matrix IP

Devices & PIC Architecture IP

Fabrication & Processing

High Speed Package & Assembly Design IP

3 Prong Strategy

Product Sales

Patent Licensing*

Technology Transfer

Goals

Make polymers ubiquitous (just like OLEDs)

Have device/PIC teams use EO polymers in their device/PIC designs

Supply polymer modulator OSAs for transceivers

Have foundries use EO polymers in PIC PDKs

Polymers in broad market verticals

***1st commercial material supply license agreement 2Q23 → market acceptance**

Source: Lightwave Logic (LWLG)


Two sides of one coin…

Is microelectronics and photonics two sides of one coin?

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- Much the same – not really (maybe silicon)
- Cut from the same cloth - (maybe silicon)
- Double-edged sword - certainly
- Two peas in a pod - certainly
- Adjacent - certainly
- Apples and oranges - absolutely
- Two of a kind – not quite, some similarities
- In the same league - perhaps
- On equal footing – not yet, maybe never
- Interchangeable – not really
- Parallel – not really
- Same, but different - perhaps
- Indistinguishable – not really

…different ways of looking at or dealing with the same situation…

Source: Lightwave Logic (LWLG), word selector, Wikiepedia (2023) Antoninianus-Tranquillina-Gordian III-s2539


Independent or symbiotic?

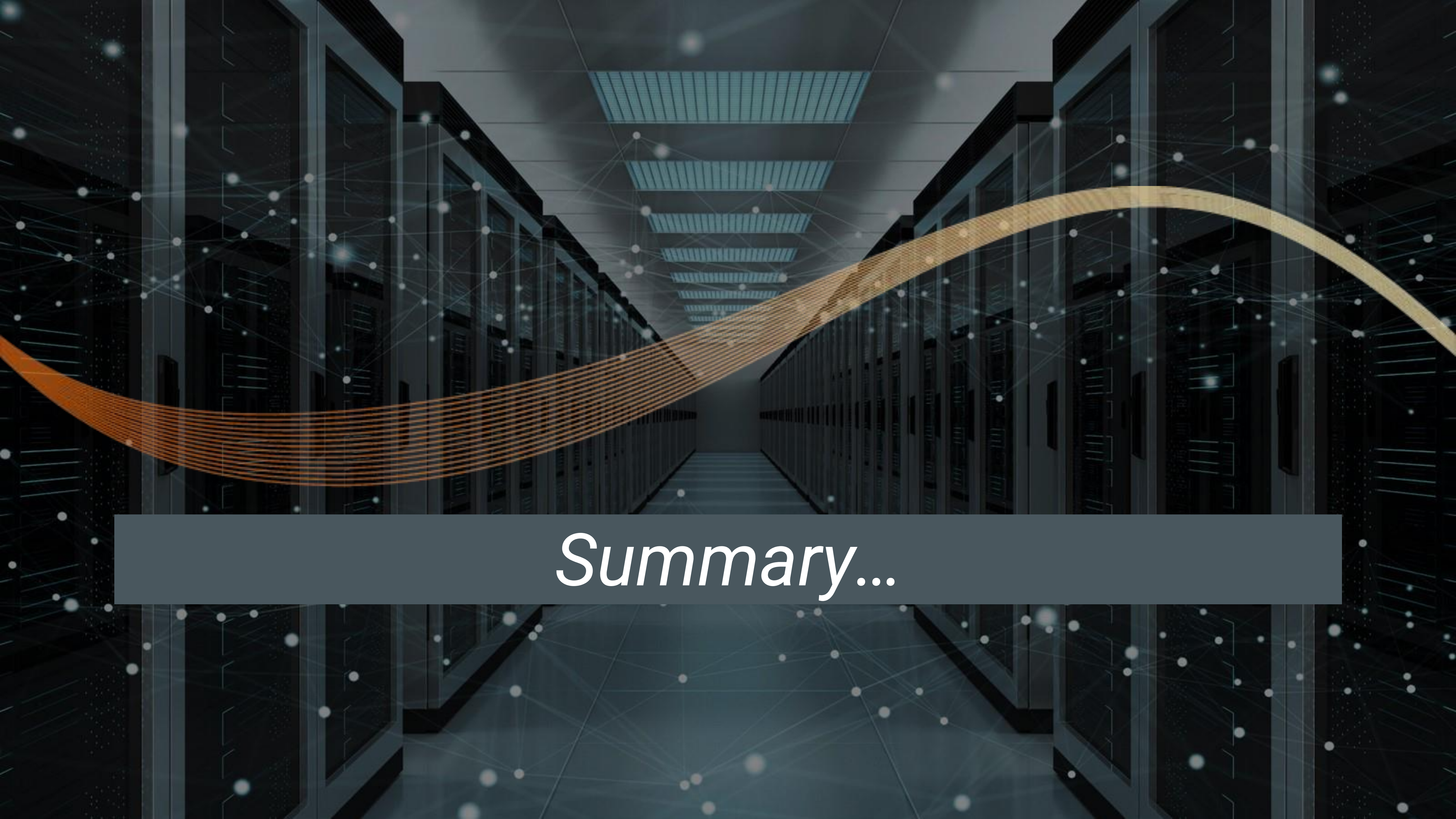
Symbiotic relationship…

- One can't live with out the other, and both need each other

…remora fish living on the shark…

Microelectronics and photonics…
…symbiotic

Source: Lightwave Logic (LWLG), https://www.treehugger.com/remora-fish-suckers-sea-inspiring-new-adhesives-



Summary...

Takeaways

- Symbiotic relationship needs upgrading for both electronics and photonics; however, G-AI is changing the playing field…the opportunity is huge…
- Industry needs higher performance packaging, modulators, lower power, higher speed, more linear electronics…
- EO polymers continue to show *technical progress with polymer reliability and stability…*
- EO polymer materials can scale today, and we are positioning to have *EO polymer modulators scale using foundries/OSATs…*

Source: Lightwave Logic (LWLG), OSAT – Outsourced semiconductor assembly and test

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LIGHTWAVE LOGIC®

Faster by Design

Thank you for listening

lightwavelogic.com

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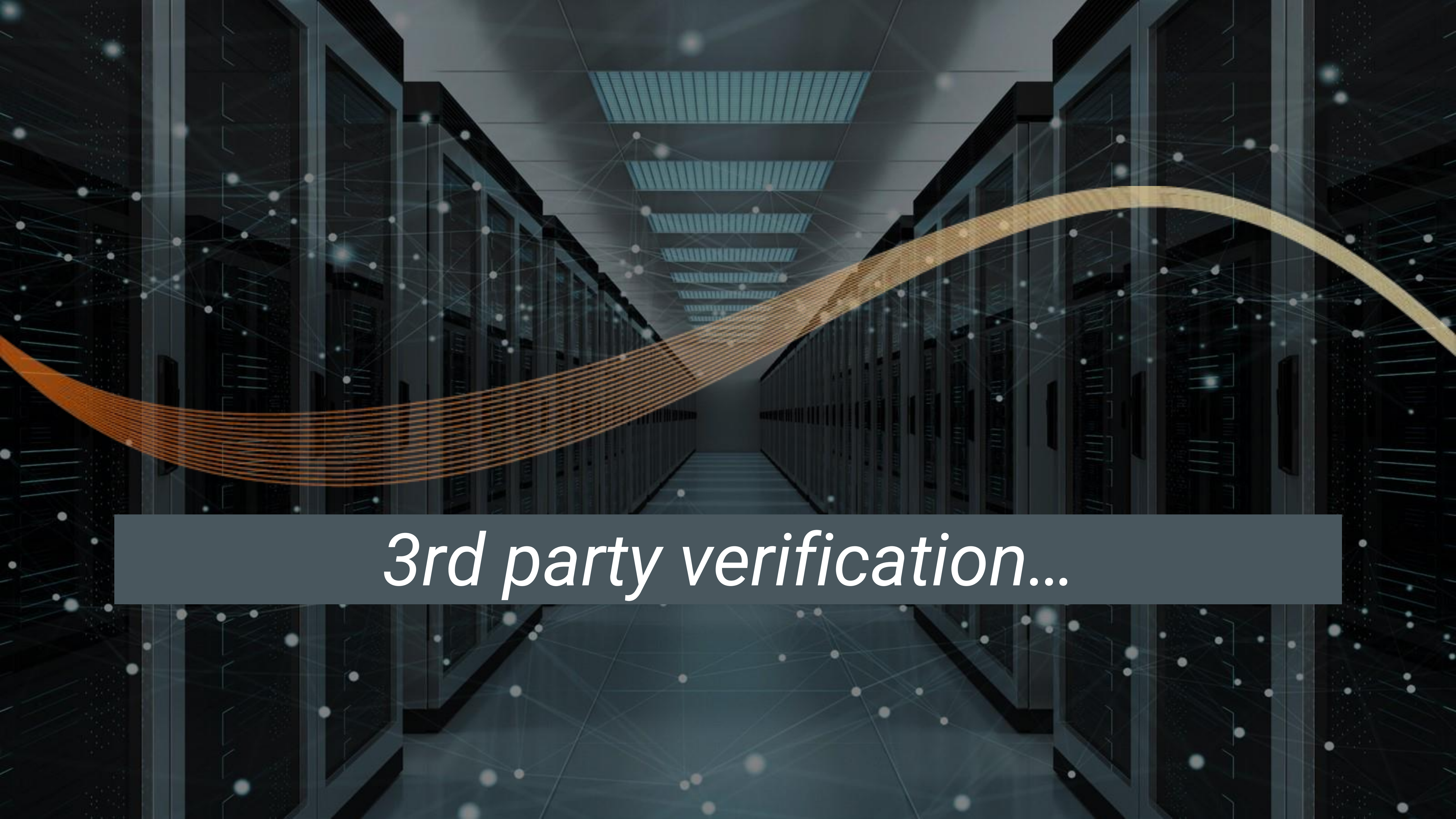
BACK-UP


3rd party verification…

3rd party use of Perkinamine®

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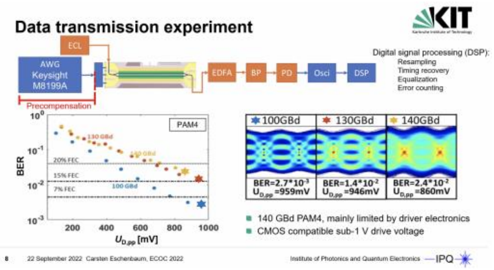
- *EO polymer* used in different device designs
- Silicon slot, plasmonic slot, plasmonic ring resonator
- All produced *world class* results*
- Presentations at *industry* conferences



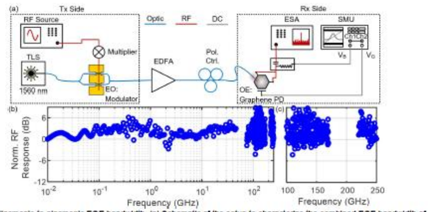
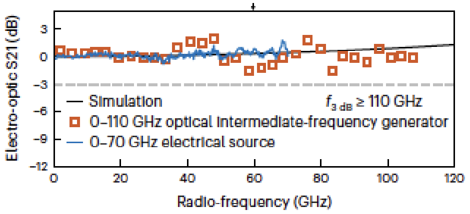
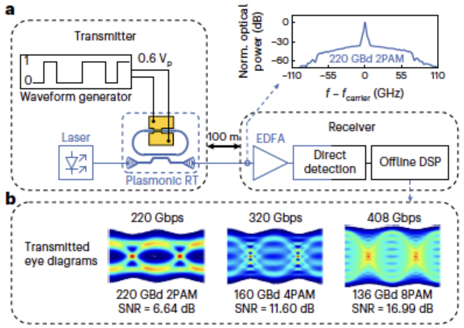


Fig. 3: Plasmonic-to-plasmonic EOE bandwidth. (a) Schematic of the setup to characterize the combined EOE bandwidth of the plasmonic racetrack modulator linked to the metamaterial graphene PD. (b) Measured normalized RF response of the system showing an EOE bandwidth of 250 GHz and (c) the response visualized from 100 to 250 GHz on a linear scale.





Sources*: Nature Photonics: Resonant plasmonic micro-racetrack modulators with high bandwidth and high temperature tolerance (ETH Zurich, Polariton and LWLG EO polymer material)

Sources*: KIT, SilOriX, EU Horizon 2020, ETH Zurich, Polariton, CAU University Kiel (post deadline paper published at ECOC2022 using LWLG EO polymers)

EO polymers are competitive with semiconductor modulators…

Competitive polymer positioning

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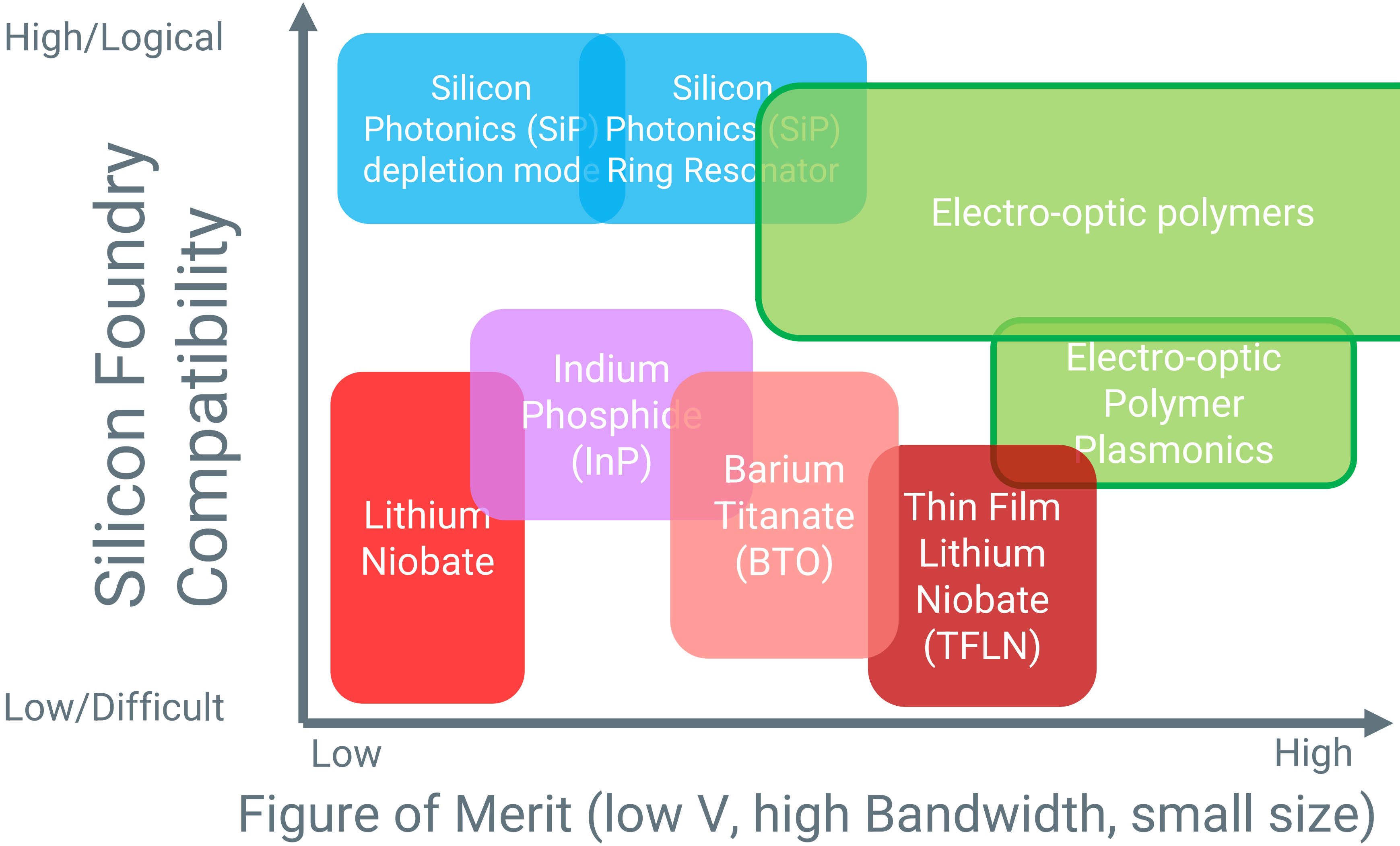

Polymer modulators outperform competitive semiconductor technologies

Source: Lightwave Logic (LWLG) research showing target metrics for polymers

Polymer attributes are impressive…

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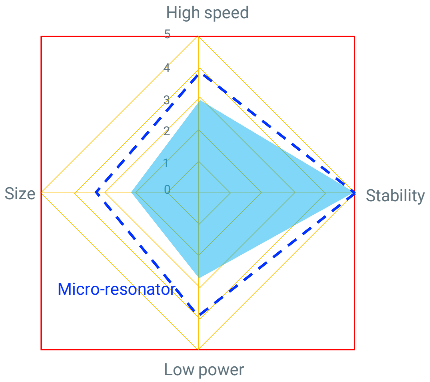
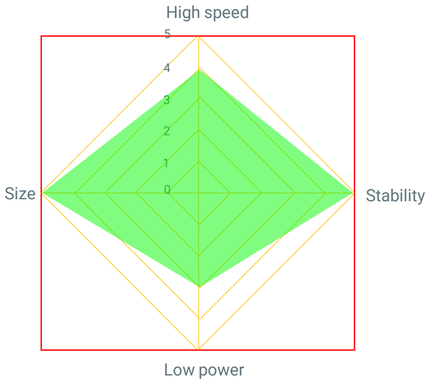
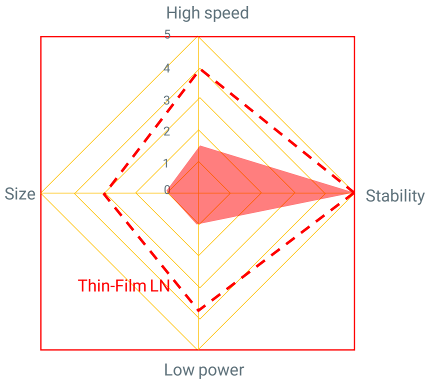
Silicon*



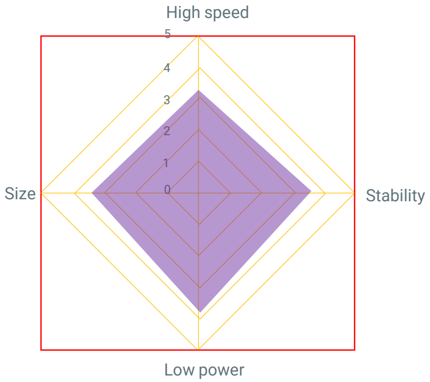
Indium Phosphide*



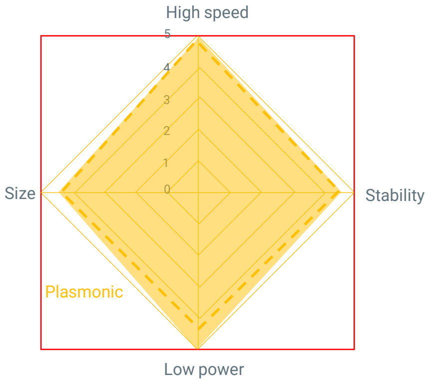
Lithium Niobate*



Barium Titanate*

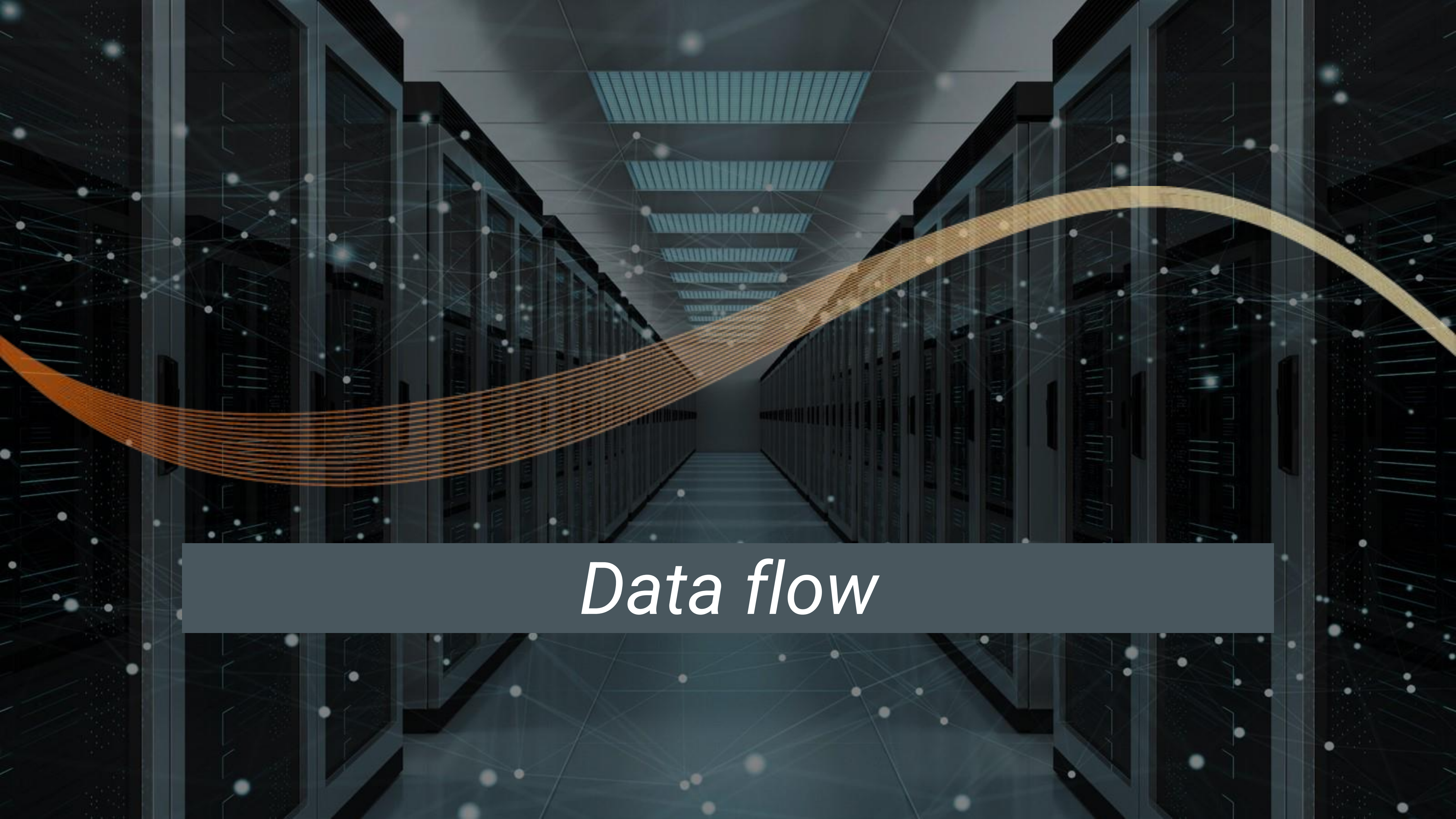


Polymer Slot*



Technology spider chart → polymers have strong coverage → excellent performance

*Source: Lightwave Logic (LWLG), *best estimates*



Data flow

Data flow…high level issues

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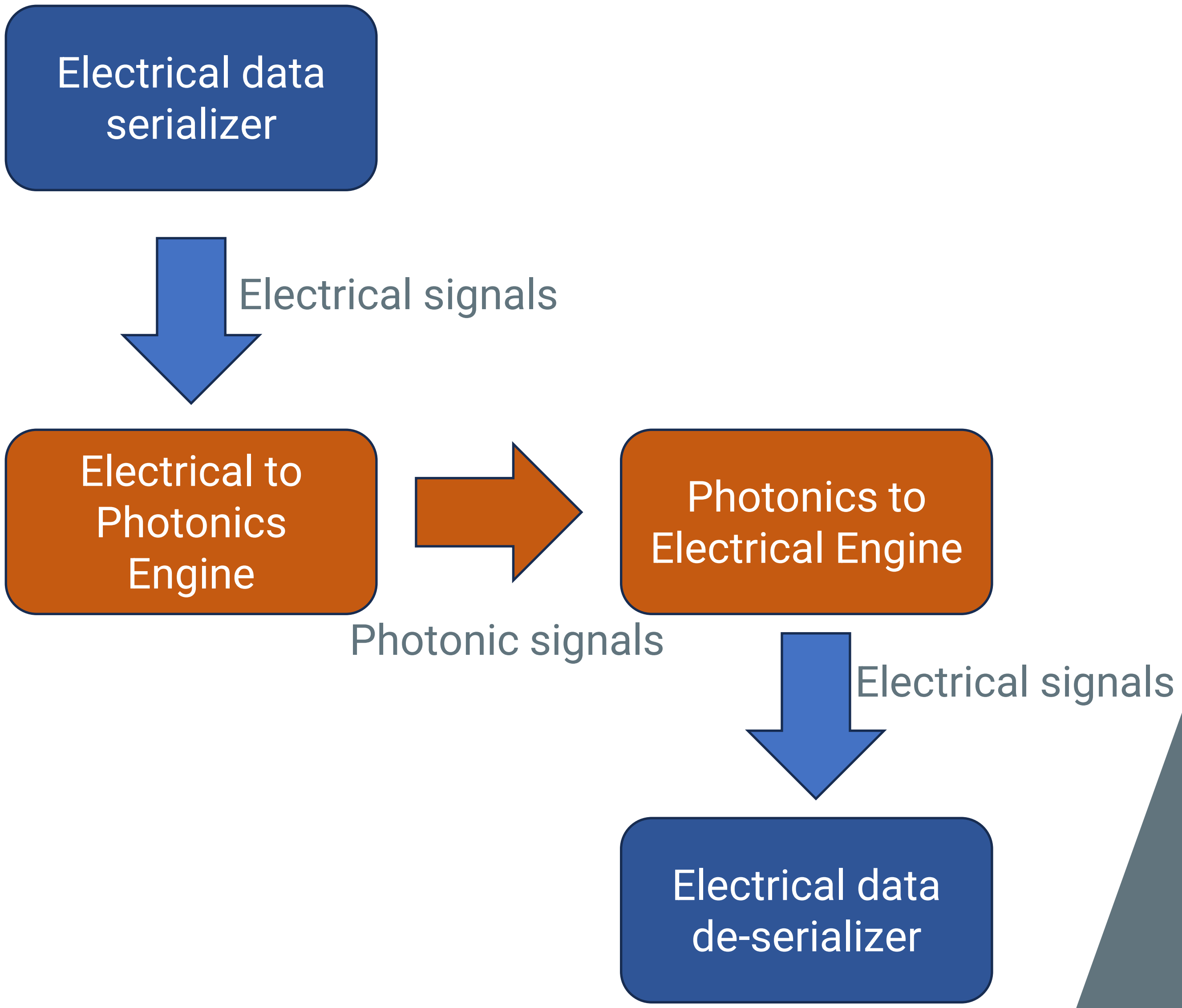

Electrical signals: high loss per distance, but low loss at interfaces

Photonics signals: low loss per distance, but high loss at interfaces

Enabled photonics market

Enabled markets of photonics

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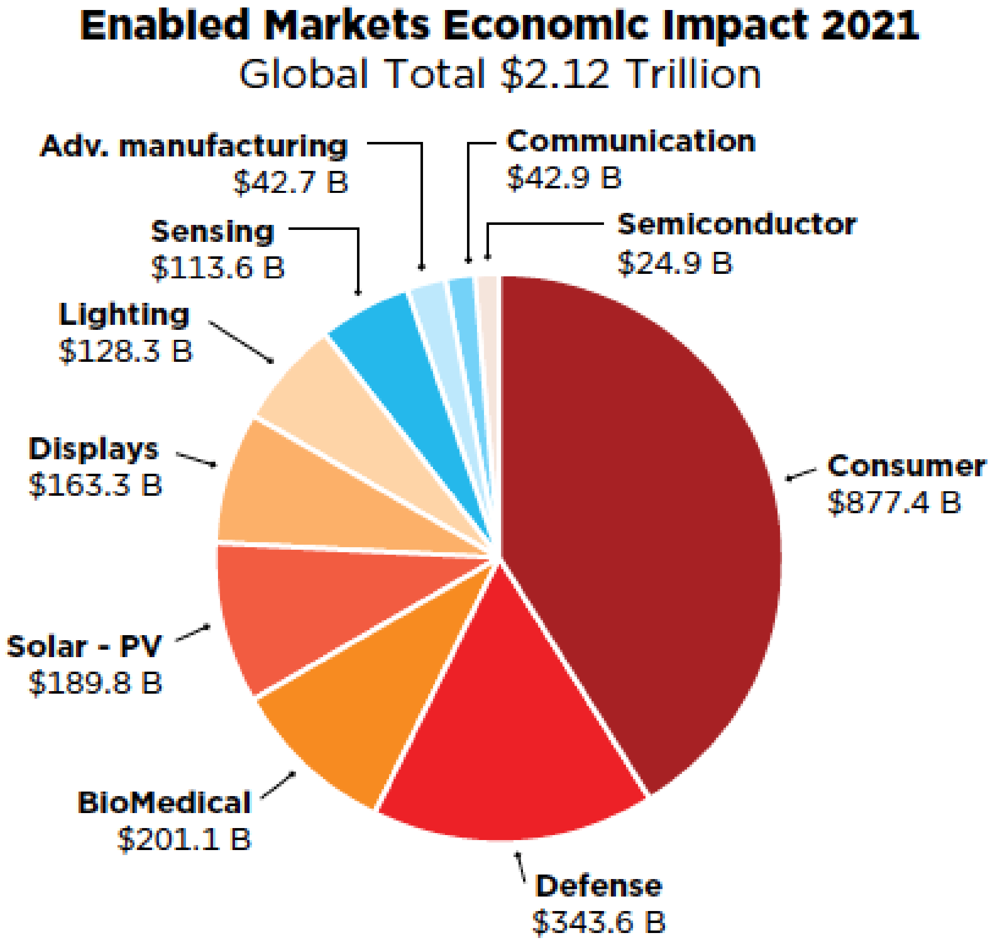

Photonics is a large and growing market

Source: Lightwave Logic (LWLG), Optics and Photonics Industry Report (SPIE 2022)