OFC Workshop 2024: Will Heterogeneous Integration Meet the Needs of Future Applications?

LIGHTWAVE LOGIC®

Faster by Design

Electro-optic polymers for heterogeneous integration

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NASDAQ

LWLG

March 2024

Safe Harbor

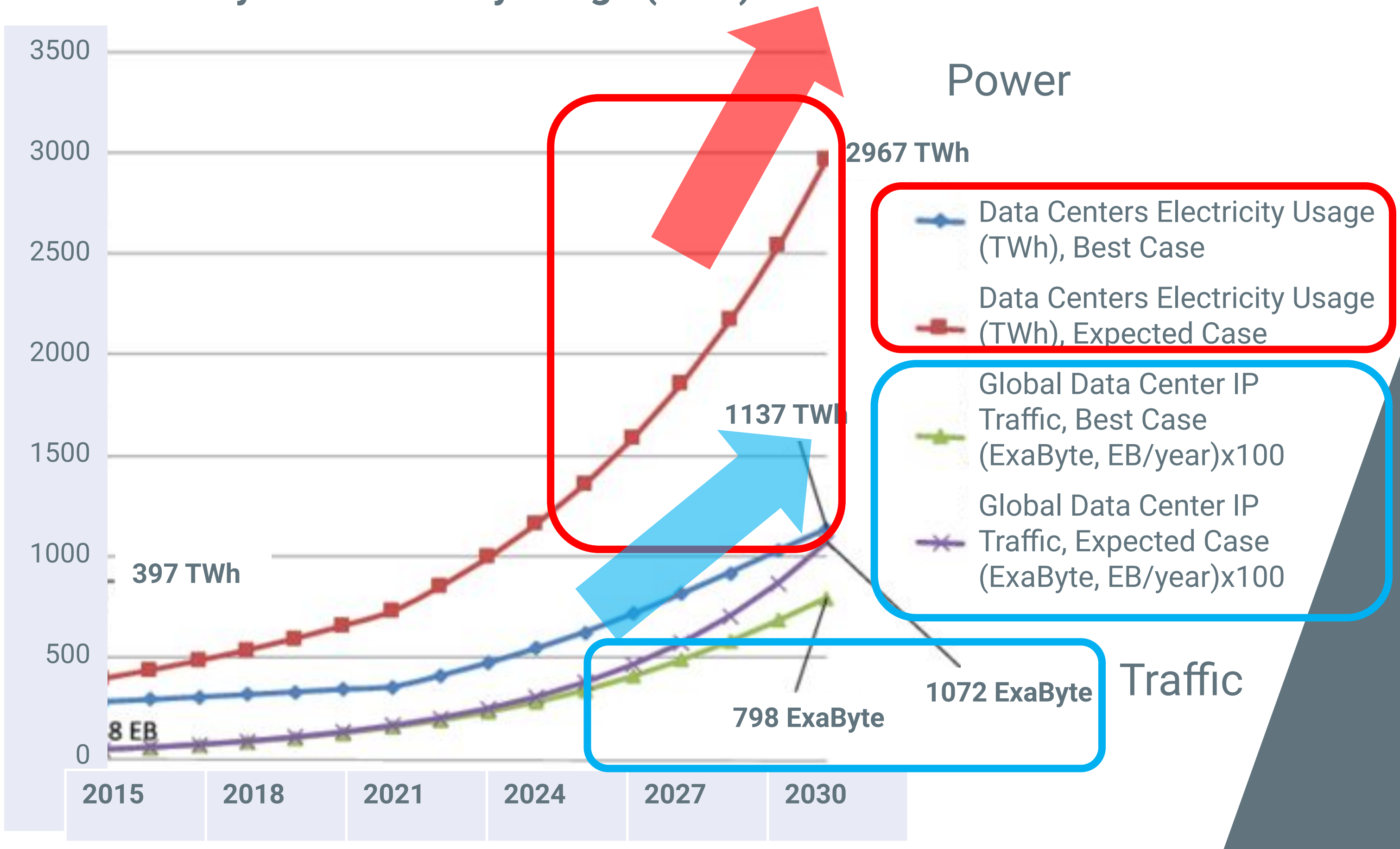
The information in this presentation may contain forward-looking statements within the meaning of the Private Securities Litigation Reform Act of 1995. You can identify these statements by use of the words "may," "will," "should," "plans," "explores," "expects," "anticipates," "continue," "estimate," "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.

The challenges…

The Achilles Heel

Existing solutions require excessive amounts of power to scale

Traffic ExaByte & Electricity Usage (TWh) of Data Centers 2015-2030



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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, hyperscalers, and service providers

Source: Publication: Walnum, HJ et al

New frontiers in electronics and photonics

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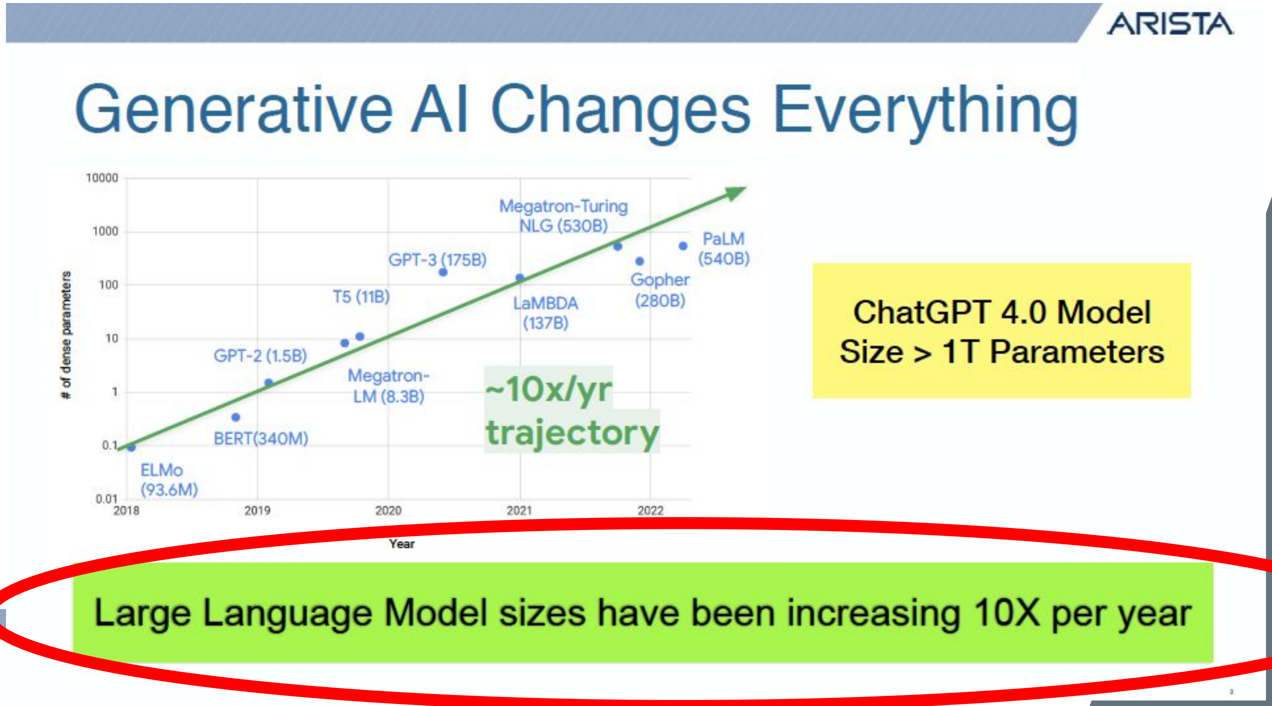
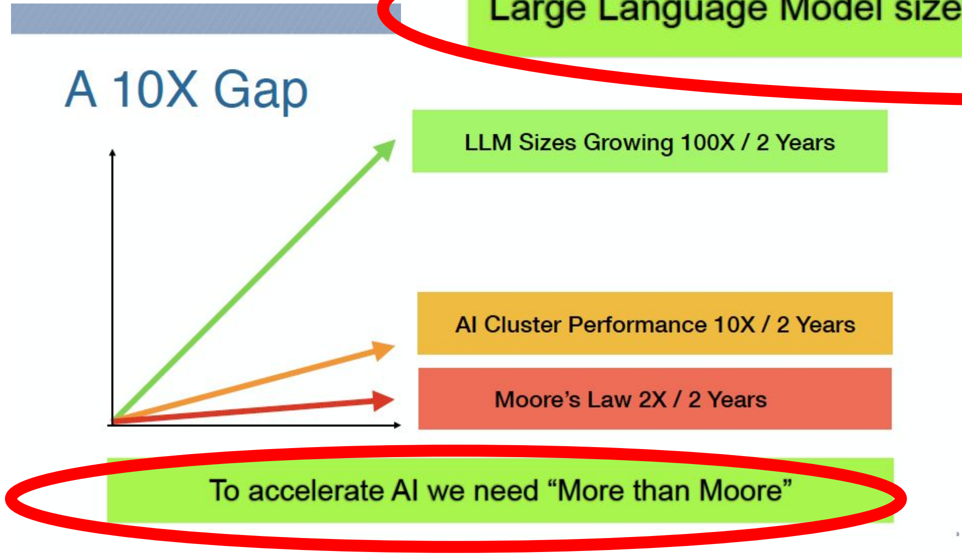
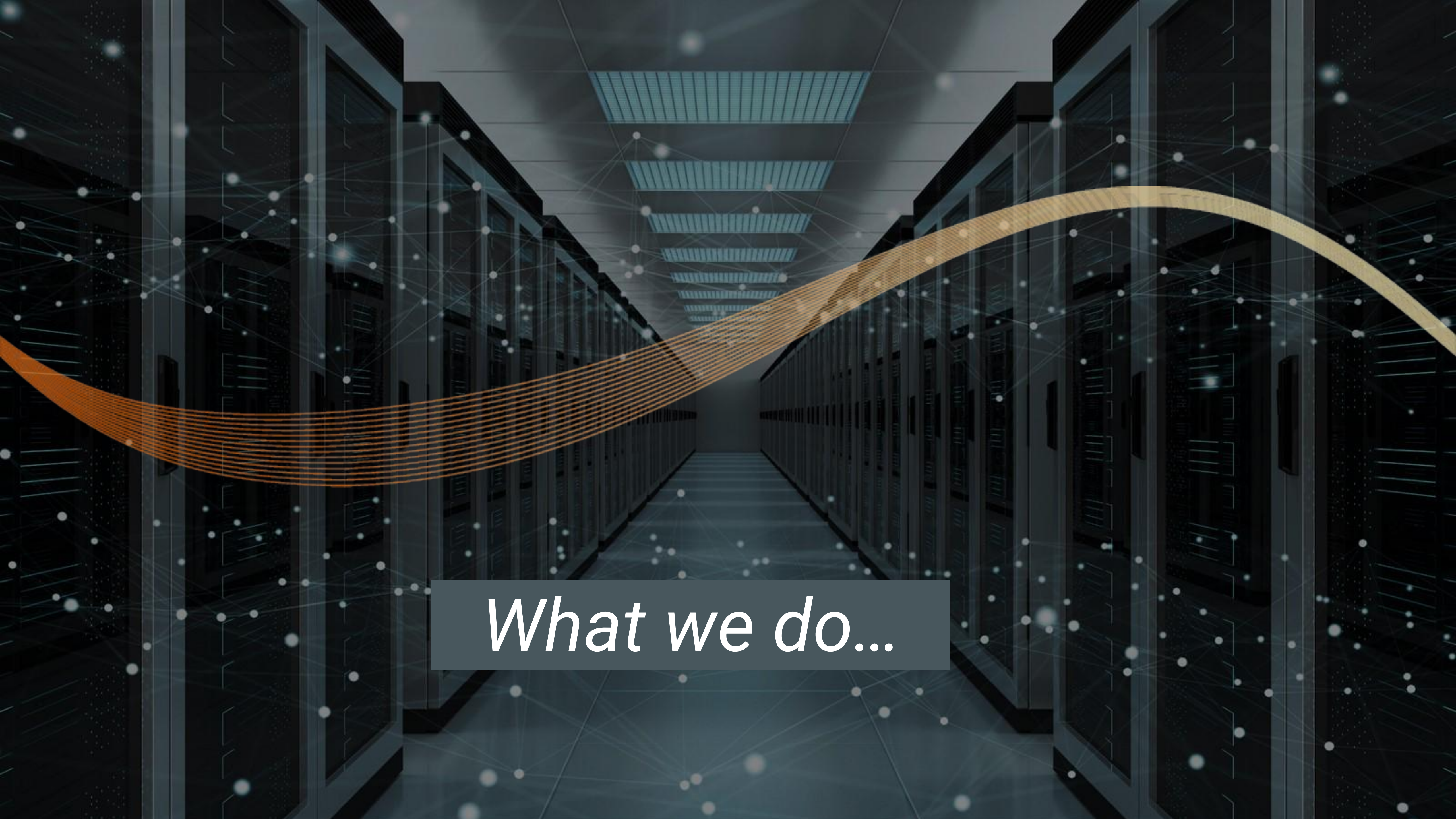




G-AI is driving new frontiers in both computational electronics and *interconnect* photonics

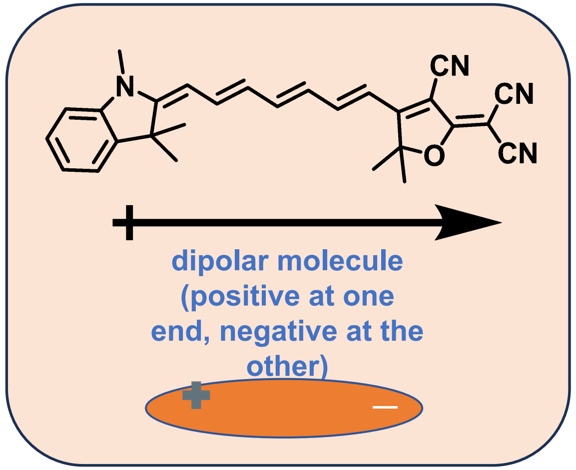
Source: Lightwave Logic (LWLG), Arista (2023)

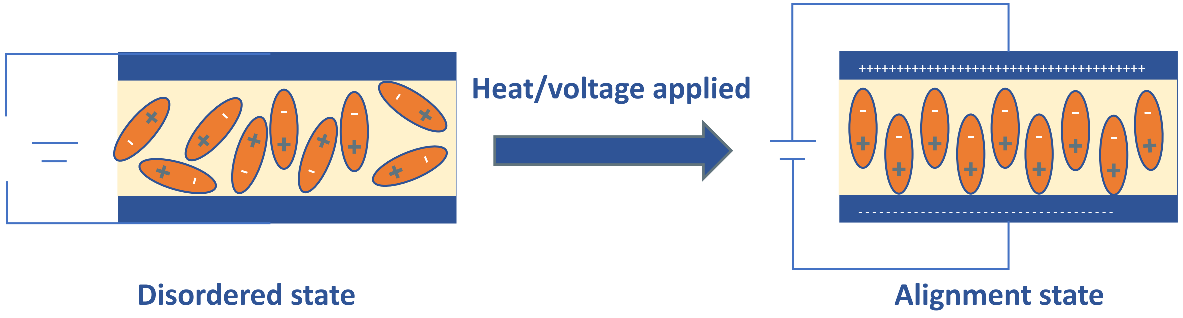

What we do…

Perkinamine® Electro-Optic polymers

Our polymers are world-class and proven by third parties

Electro-optic polymers can be used to fabricate optical modulators





We create organic chromophores...

- Designed, simulated and modeled in Denver, Colorado
- Manufacturing chemistry facility that can scale volume
- Deep experience with material characterization, testing, lifetime, and reliability

Polymer modulator opportunities

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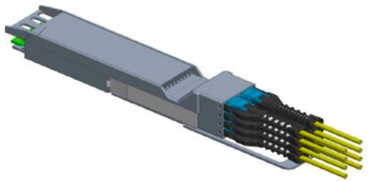
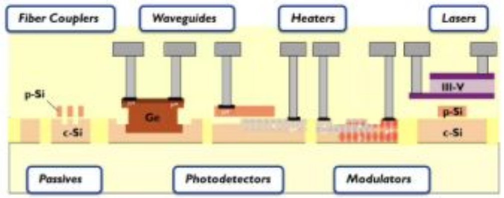
Electro-optic polymer modulators for transceivers suppliers

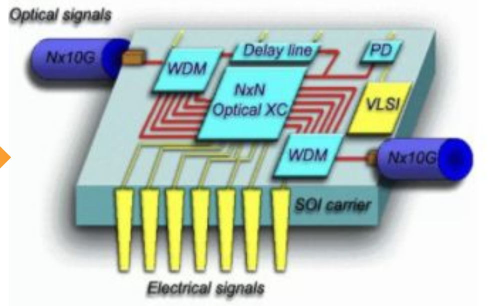


Electro-optic polymer modulators for Silicon Photonic platforms



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

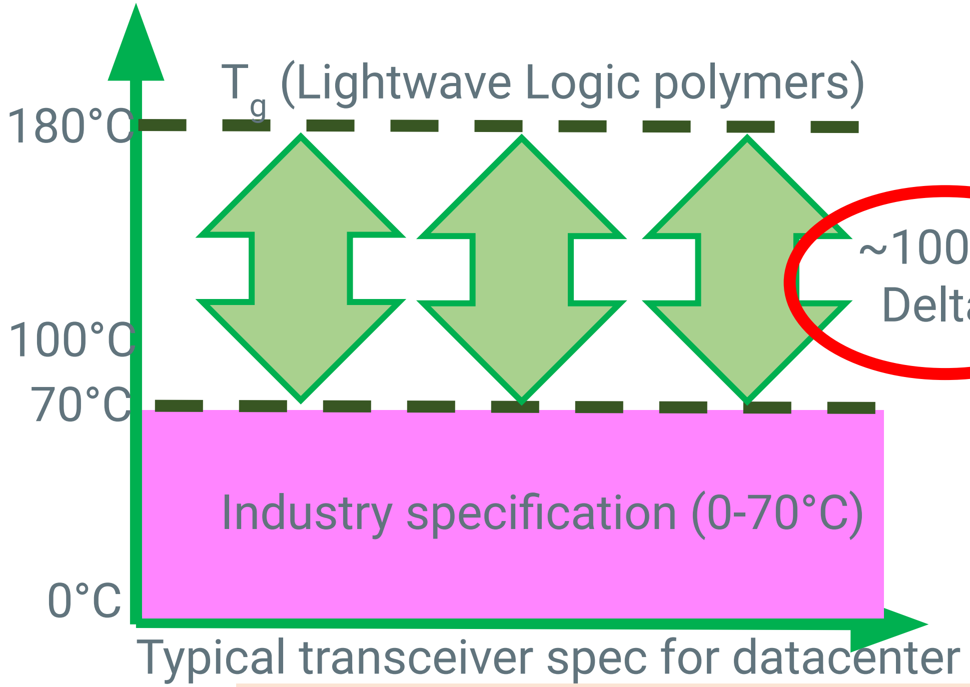
Source: Ethernet Alliance, OSFP MSA, https://www.researchgate.net/figure/Schematic-of-an-on-chip-optical-network-with-various-components-illustrated-including_fig2_239929876, ePIXfab, corning

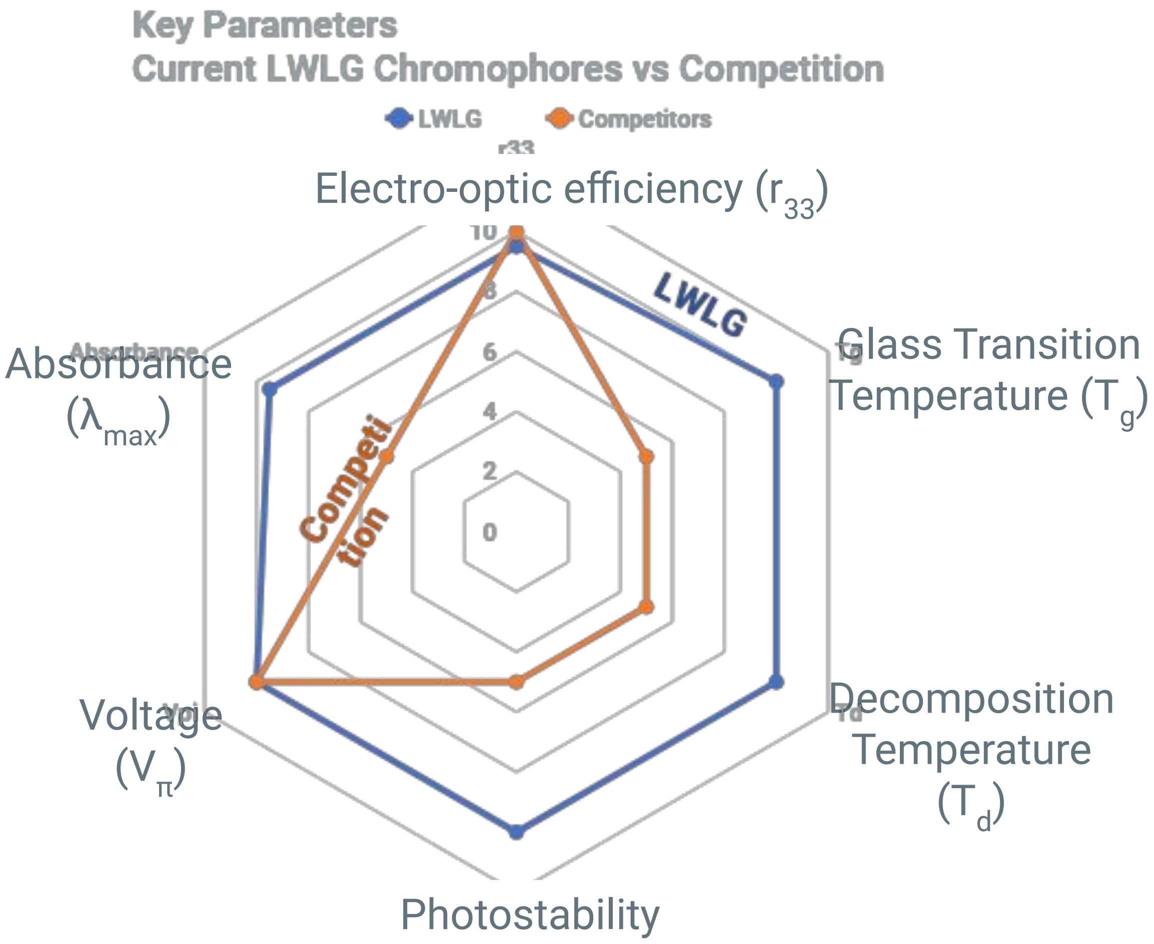
EO Polymer material robustness…

Design philosophy: optimized reliability & performance

LIGHTWAVELOGIC®

- **World class chromophore design**
  - Very high glass transition temperature (T_g) □ increases EO material lifetime
  - ~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)



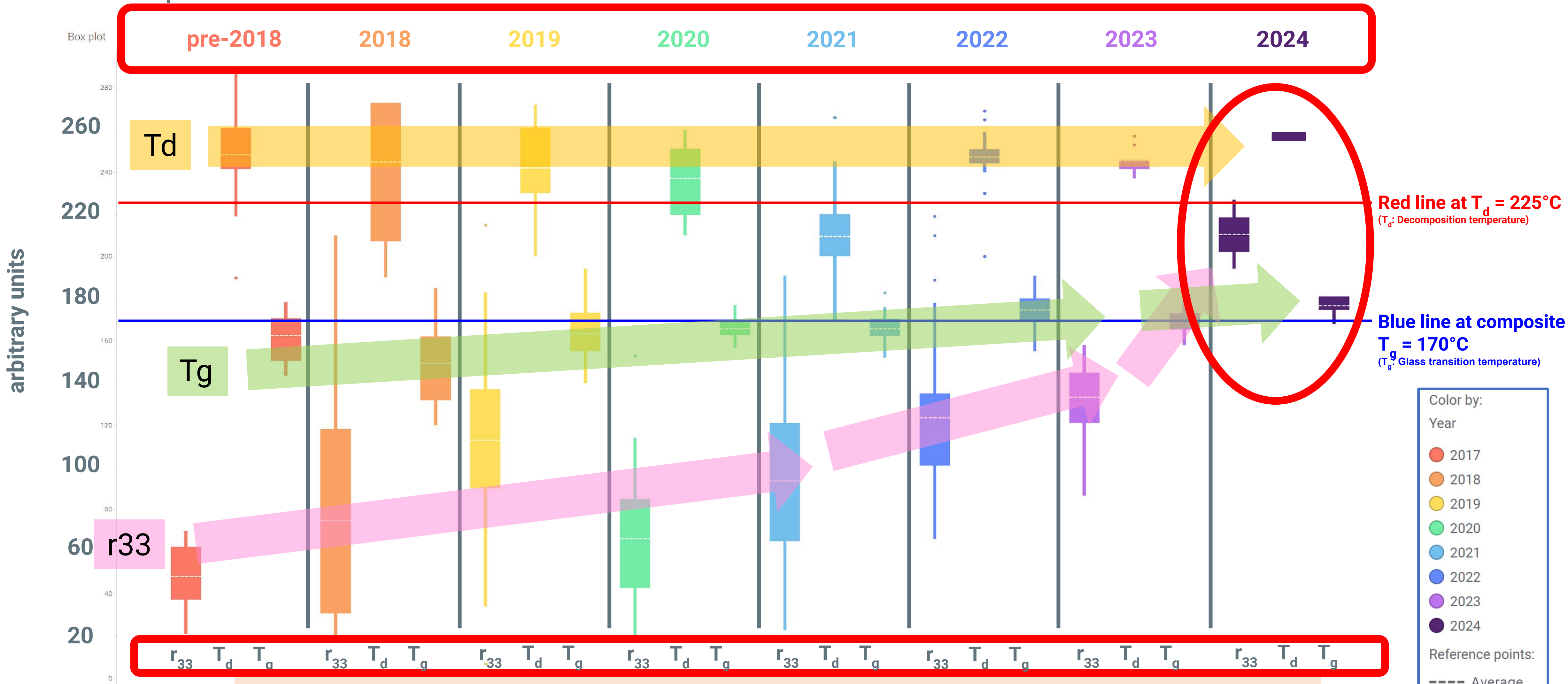


Electro-optic material designed for reliability, stability, and overall operational performance

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.

LWLG EO polymer materials have significantly improved…

Box plot of Perkinamine®



Tracking r_{33}, decomposition temperature, 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


Heterogeneous integration of
polymers with silicon…

Polymers are ideal for silicon foundries…

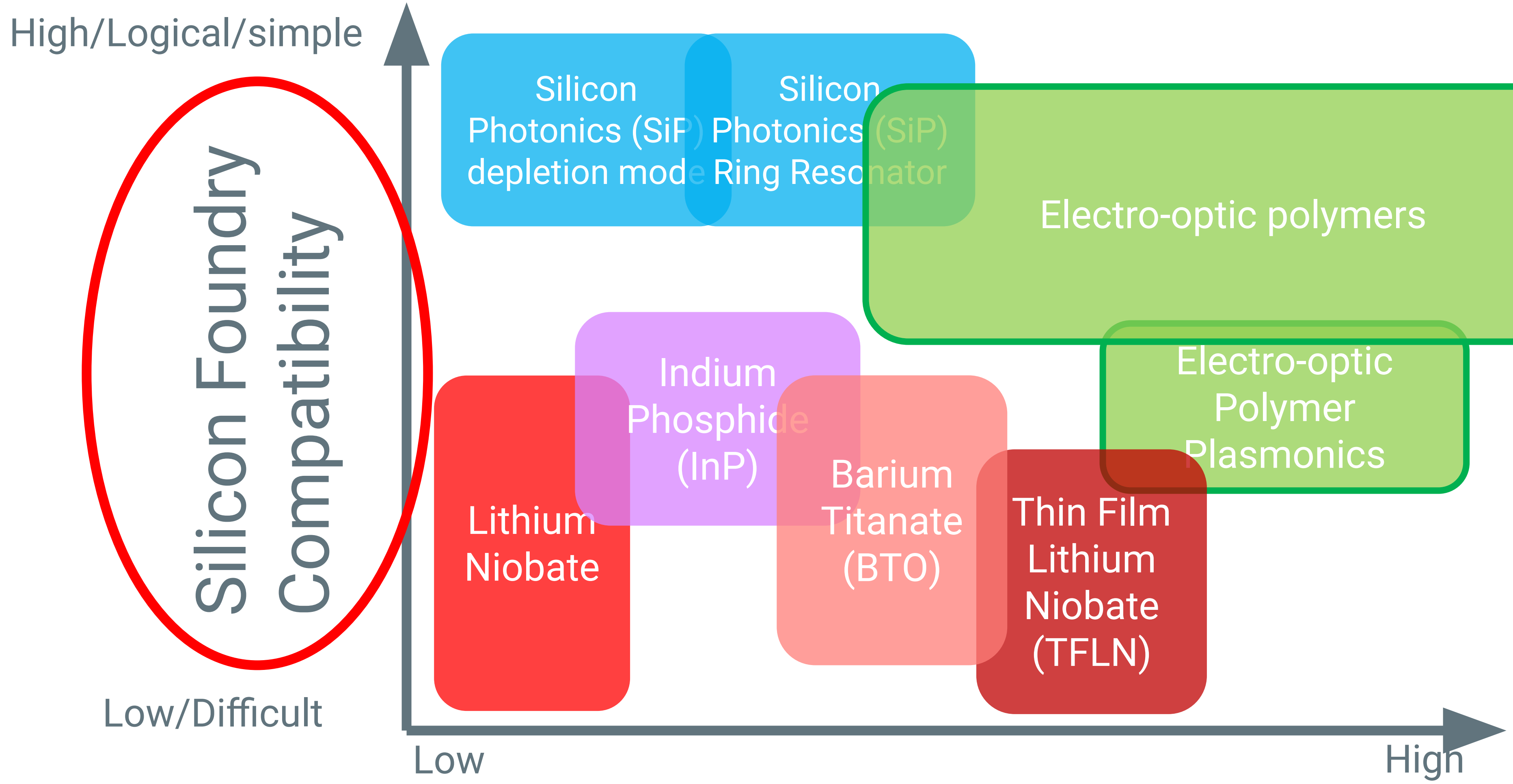


Figure of Merit (low V, high bandwidth, small size, ease of PDK, fabrication)

Polymer positioning for heterogeneous integration is aligns with silicon foundries very well

Silicon foundry 200mm Silicon wafers

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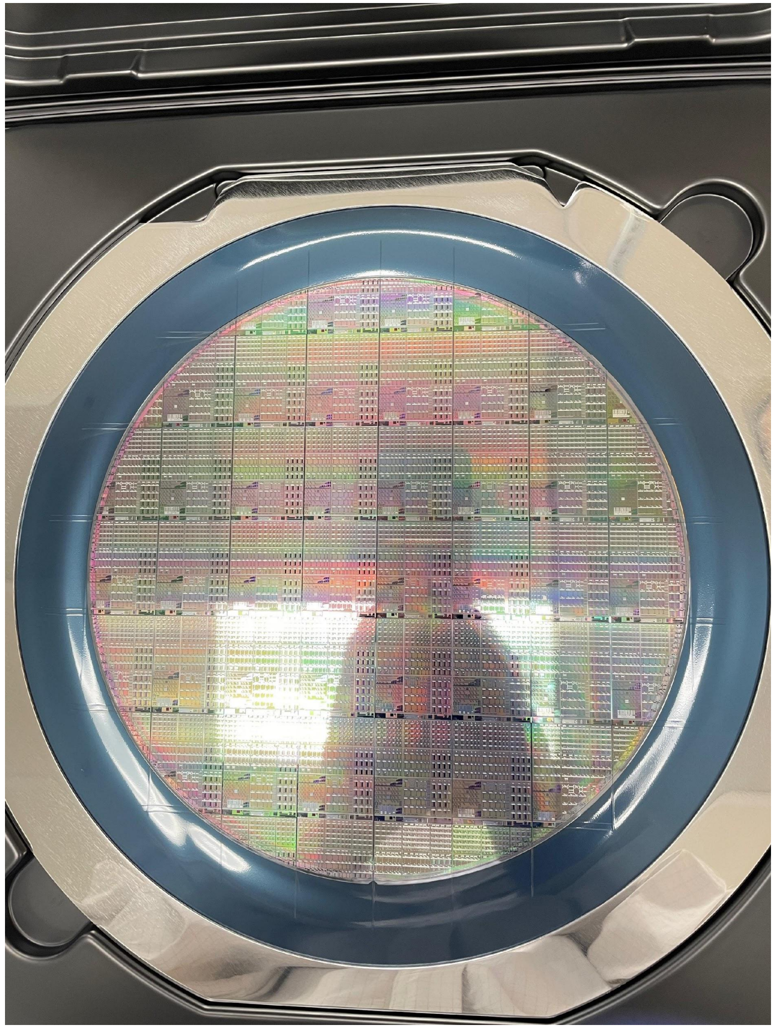

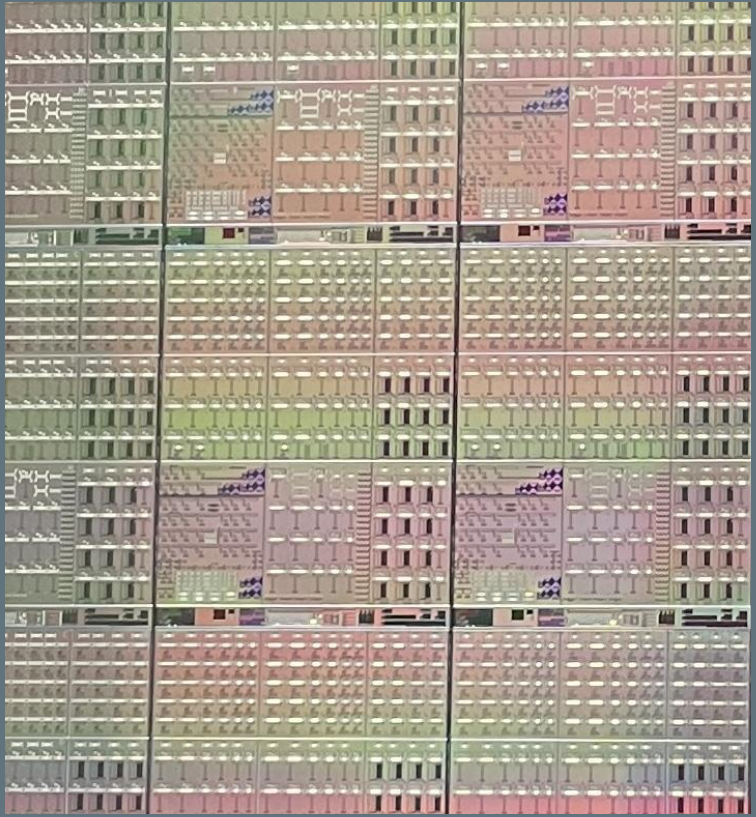

Volume scale silicon slot designs on 200mm wafers

Heterogeneous Polymer Slot Modulator

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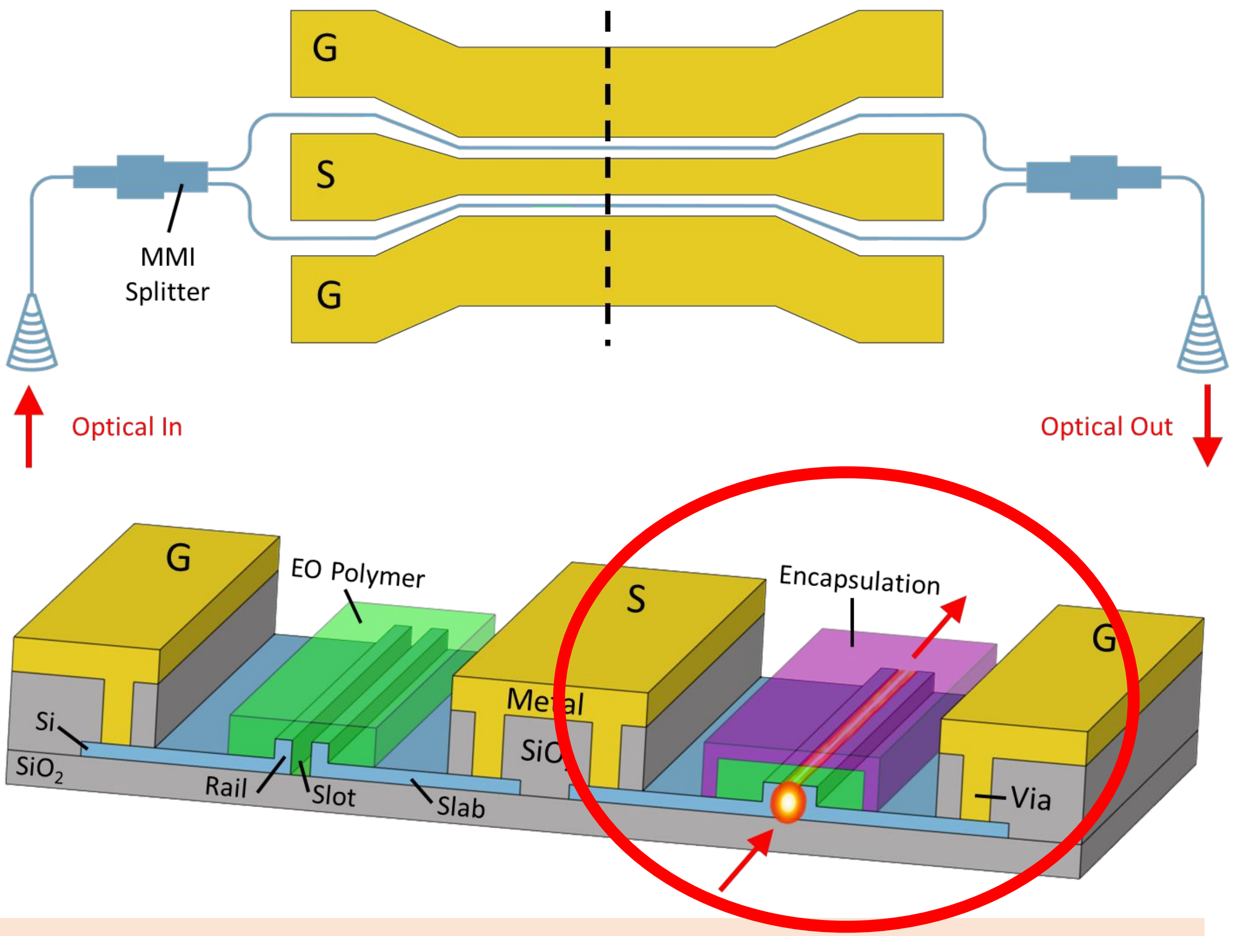
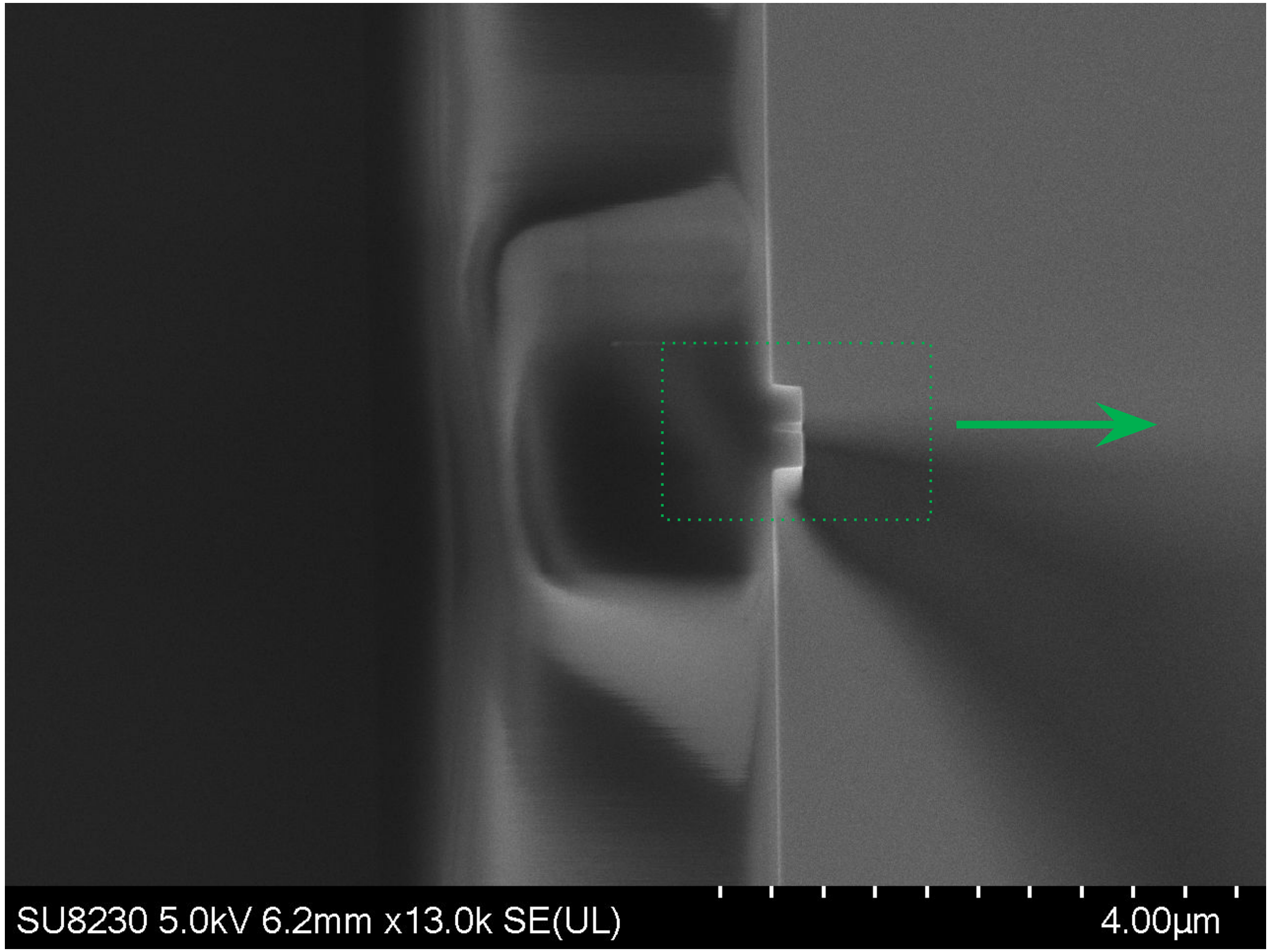
Our polymers are ***easily fabricated*** in silicon fabs □ ideal for heterogenous integration

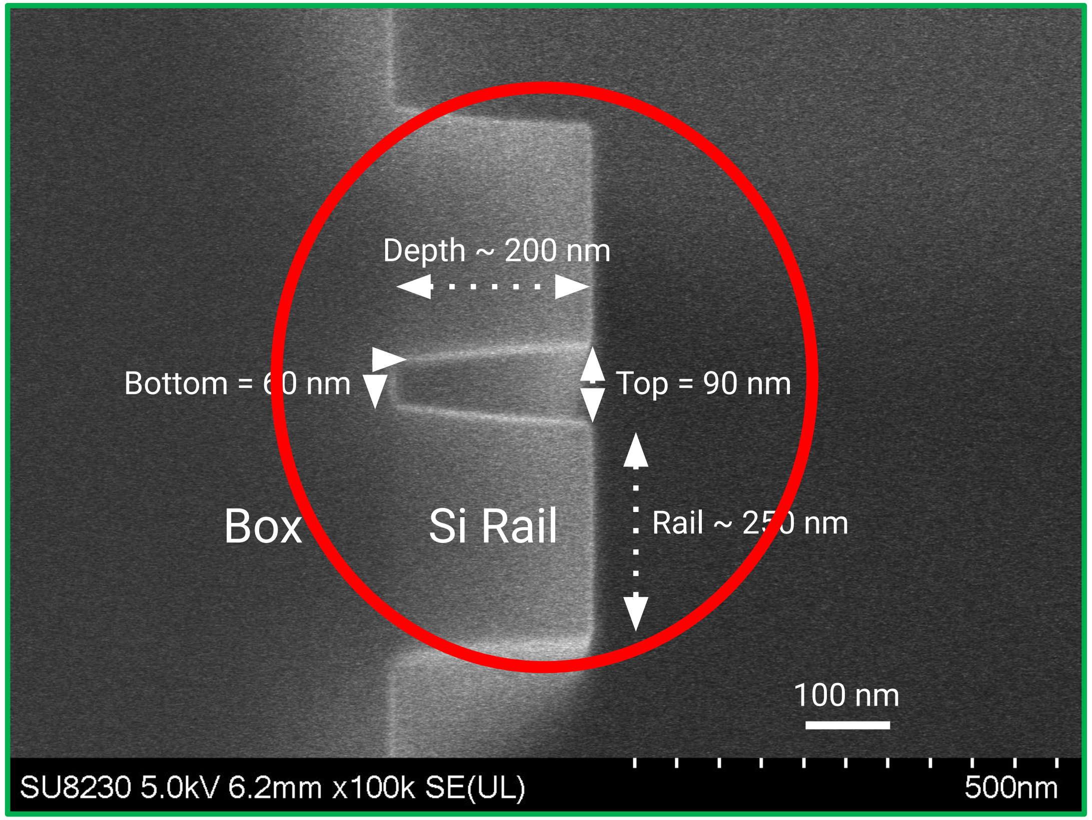


EO polymer heterogeneous integration onto silicon wafers

- **Heterogeneous integration of polymer on Silicon Photonics Platform**
- **Low drive voltage and small form factor for low power consumption and high density**
- **Very high bandwidth (70-100GHz)**

Cross-section of fully etched slot waveguide





Clean, sharp silicon slots with width <100 nm, sidewall angle > 86°

Heterogeneous integration of polymer and silicon

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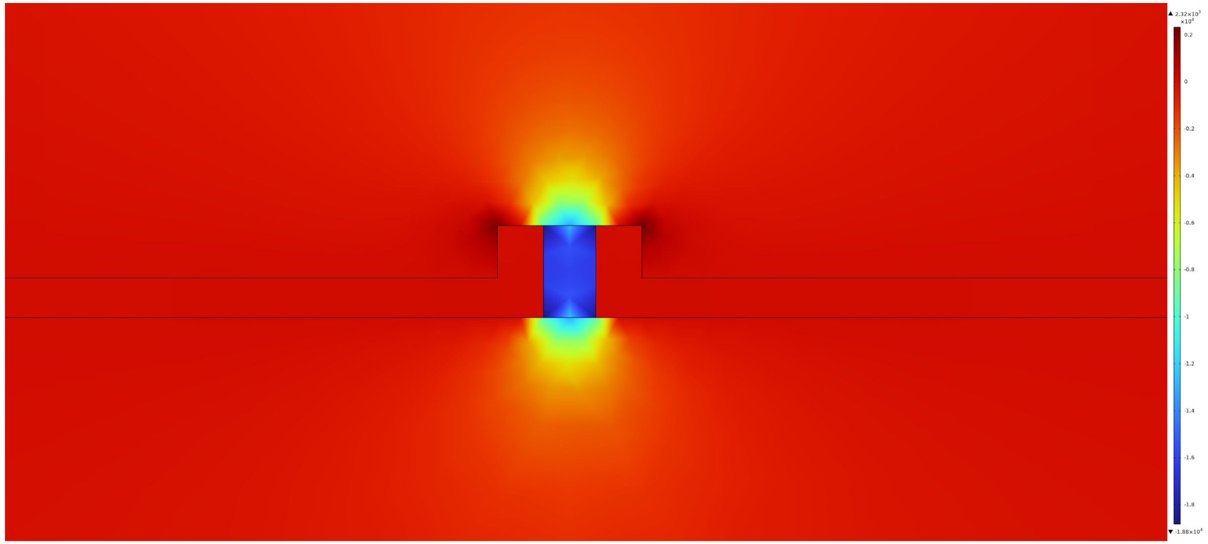
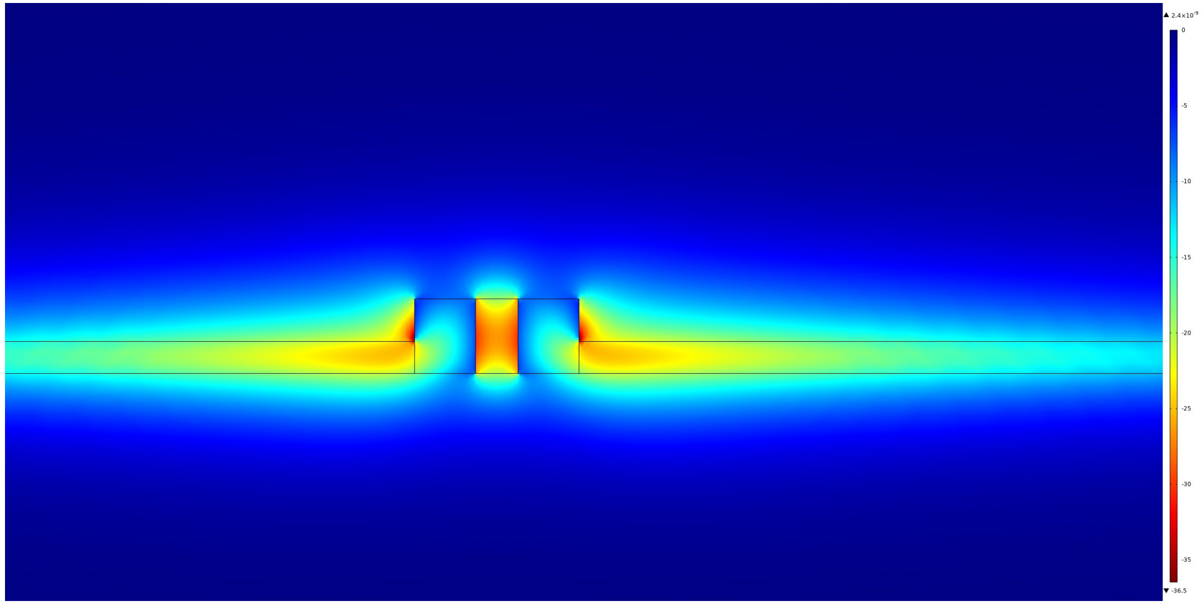


E-field simulation

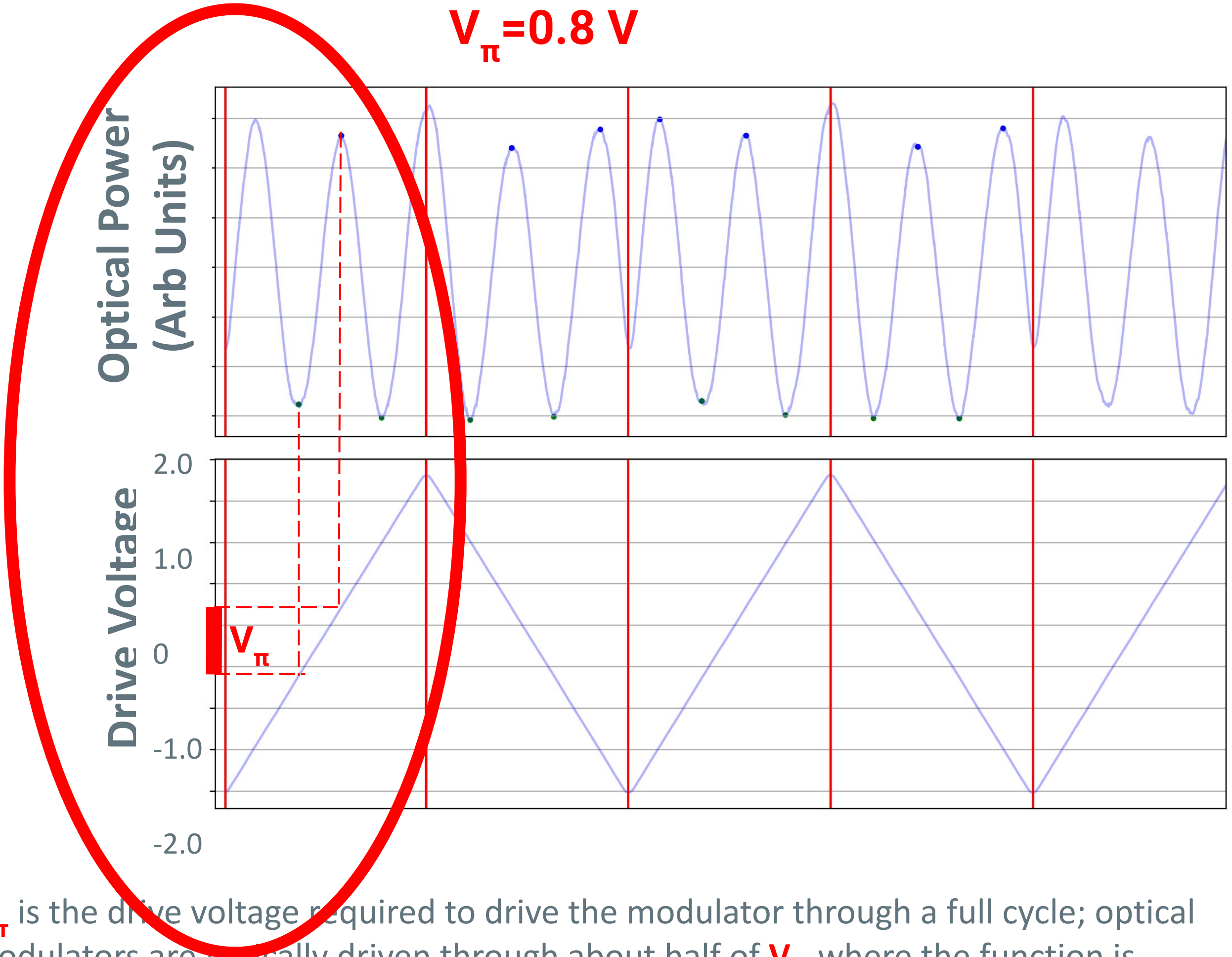


Optical mode simulation

Low voltage drive polymer slot modulator

Modulator Transmission Function

V_π=0.8 V

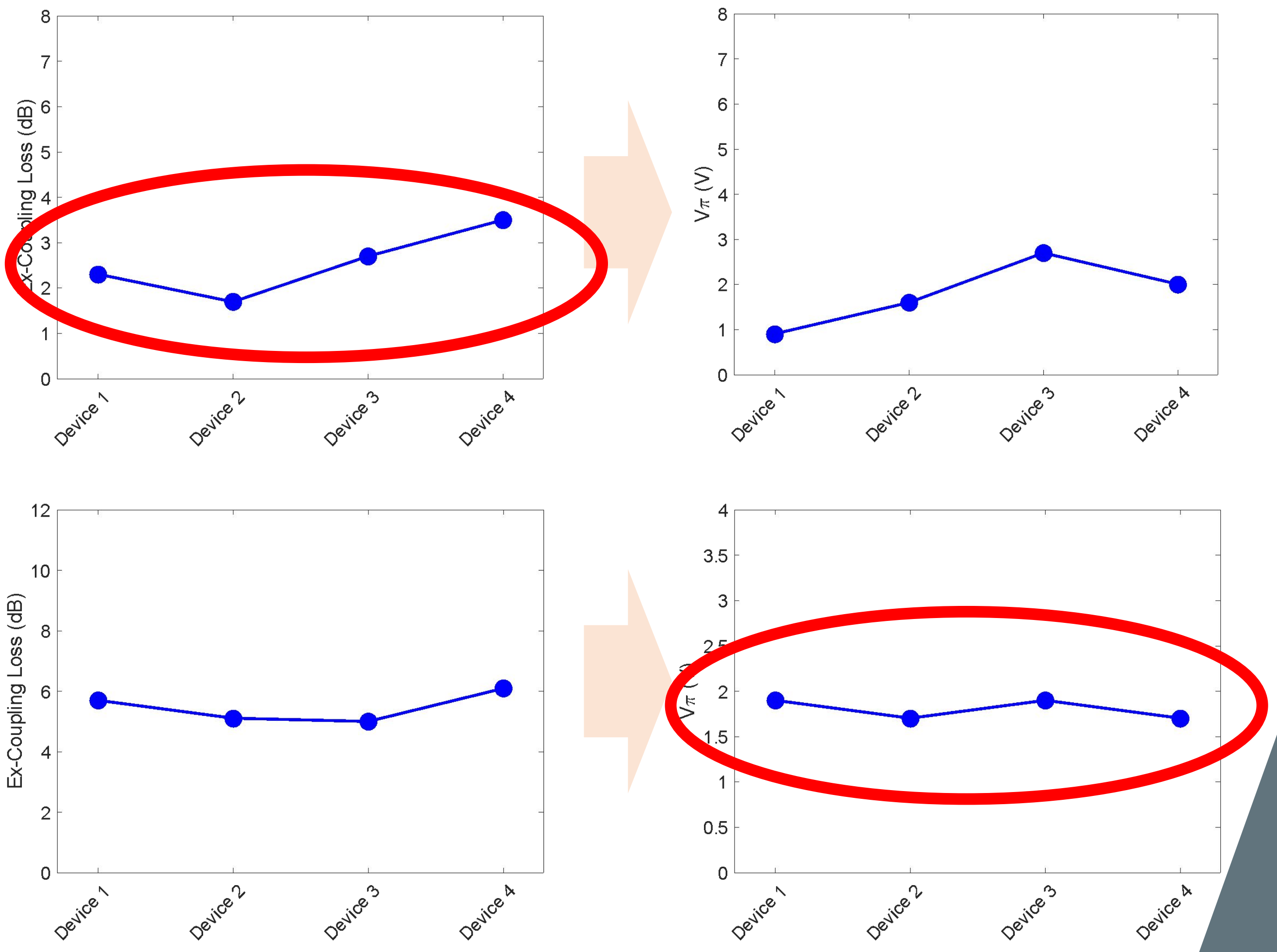


V_π is the drive voltage required to drive the modulator through a full cycle; optical modulators are typically driven through about half of V_π where the function is linear

- **Very low drive voltage**
- **Can be directly driven from CMOS**
- **Fabricated onto 200mm silicon wafers**

Designed for very low power consumption (<1V)

Packaged slot modulator performance

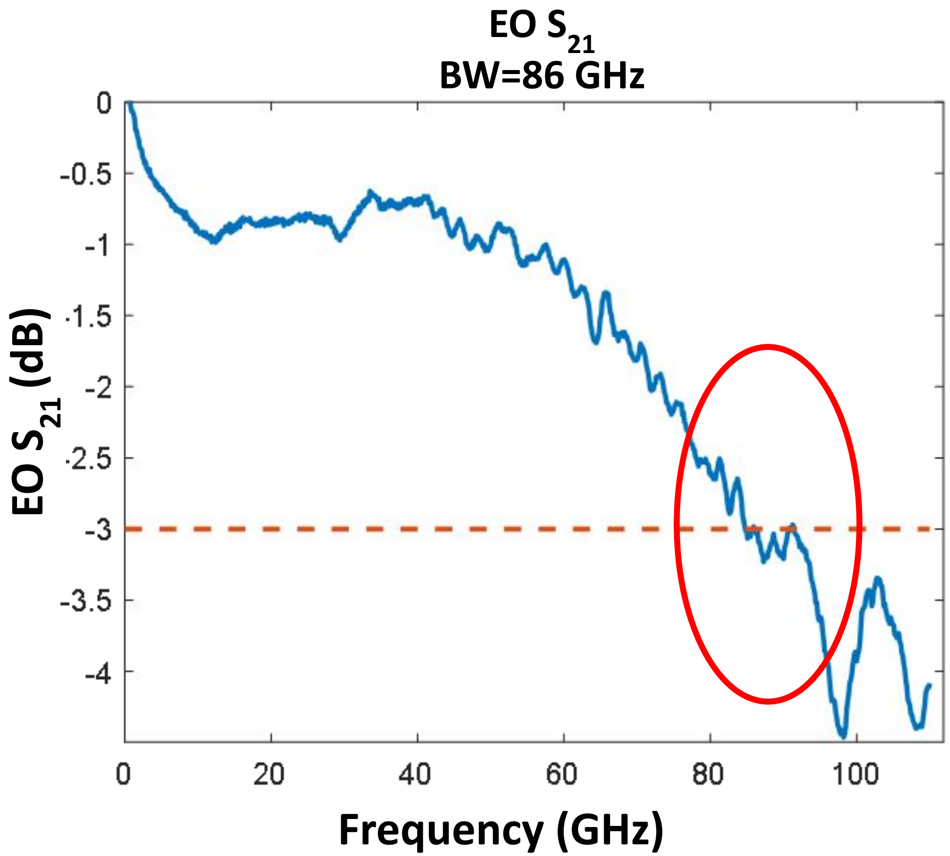


- Uniform low ex-coupling loss across 4 packaged devices
- Uniform low Vπ across 4 packaged device

Uniform ex-coupling loss and V_{π} polymer performance

High BW MZ Polymer Slot™ Modulator

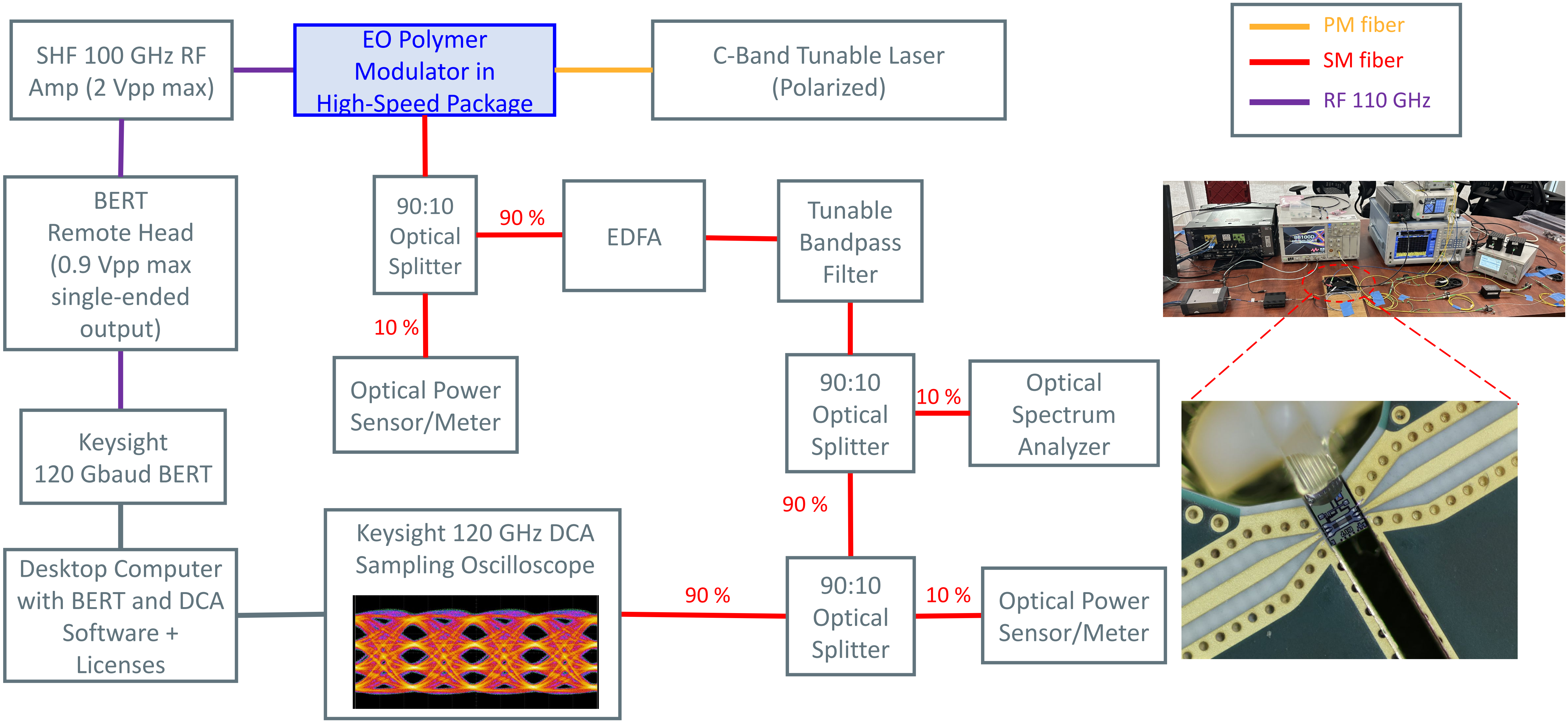
LIGHTWAVELOGIC™



EO Bandwidth=86 GHz
EE Bandwidth>110 GHz

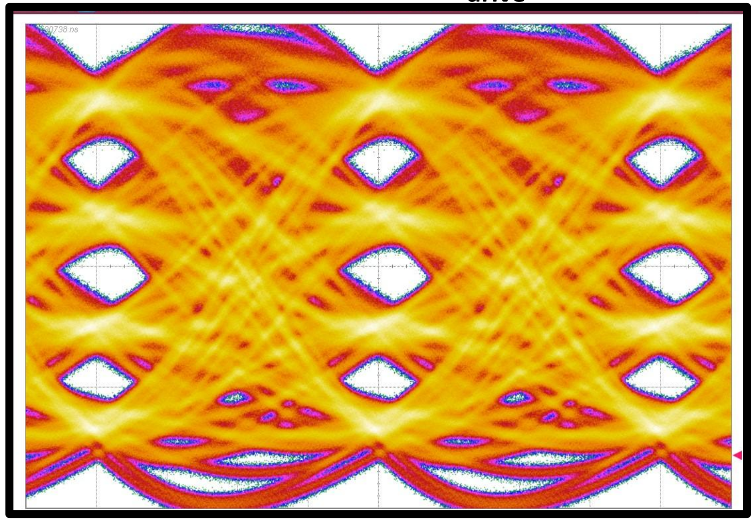
Enables optical signaling for >200Gbps lanes

Packaged polymer modulator demo schematic

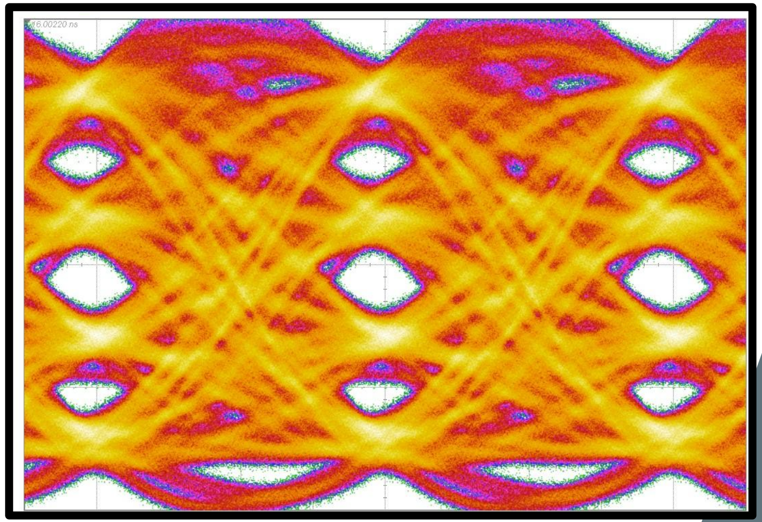


200Gbps packaged polymer slot

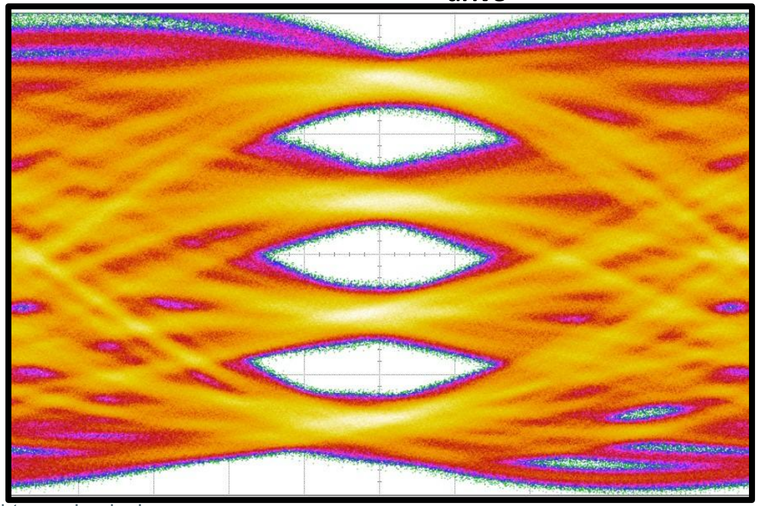
90 Gbaud, 180 Gbit/s, V_{drive} < 2 V



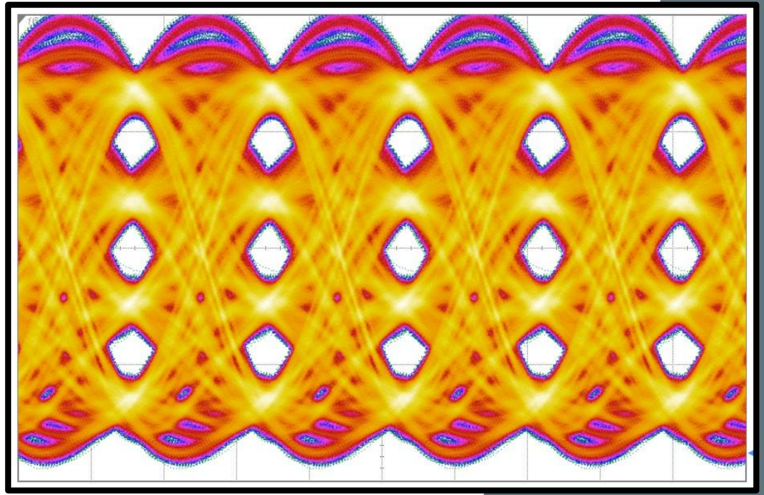
100 Gbaud, 200 Gbit/s, V_{drive} < 2 V



53 Gbaud, 106 Gbit/s, V_{drive} < 2 V



53 Gbaud, 106 Gbit/s, V_{drive} < 2 V



Drive Voltage <2V

Up to 100GBaud PAM4 (200Gbps)

Open eyes…

Open eyes…

Open eyes…

3rd party use of Perkinamine® LWLG polymers

- *EO polymers* used for *400Gbps lanes* in plasmonic slot devices
  - Paper to be presented this week at OFC (W4H.5)
- *Potential for* 4 channel x 400Gbps pluggable transceiver at 1.6Tbps (1600Gbps).

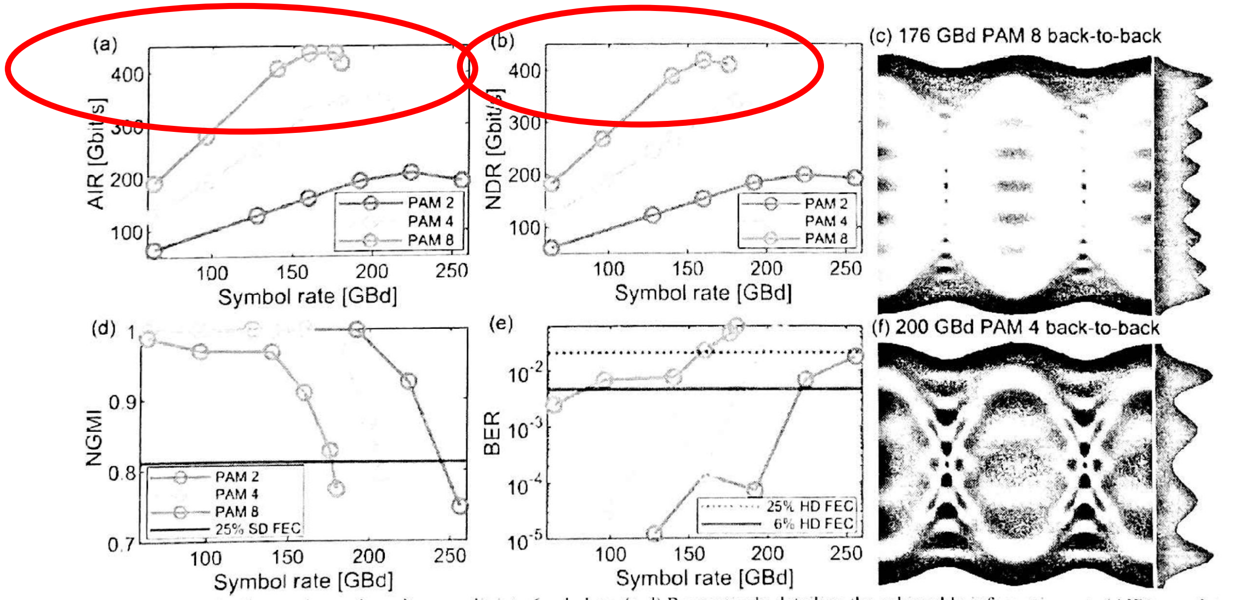


Fig. 2 Back-to-back experimental results are split into 6 subplots. (a-d) Respectively detailing the achievable information rate (AIR), net-data rate (NDR), normalized general mutual information (NGMI) as well as bit-error rate (BER) for the back-to-back measurements. (e-f) Showing the achieved eye-diagrams for the 176 GBd PAM 8 signal reaching the highest AIR and the 200 GBd PAM 4 signal.

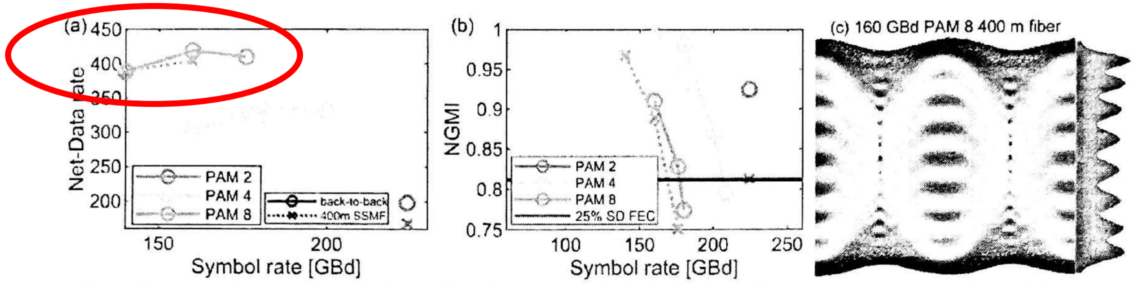


Fig. 3 Comparison between back-to-back and 400 m fiber transmission is detailed in (a & b). Respectively showing the net-data rate and normalized general information (NGMI) for the back-to-back (solid lines) as well as the 400 m fiber transmission (dashed lines). (c) Showing the achieved eye-diagrams for the 160 GBd PAM 8 signal reaching the highest data rate after fiber transmission of 404.5 Gbit/s.

NB: Paper to be presented at OFC 2024: Presentation ID: W4H.5 Paper Title: Single Carrier net 400 Gbit/s IM/DD over 400 m Fiber Enabled by Plasmonic Mach-Zehnder Modulator

Sources: ETH Zurich, Kulmer et al, OFC 2024 (W4H.5), LWLG Perkinamine™ chromophore series 3 material

Reliability

Modulator Thermal Stability (TS)

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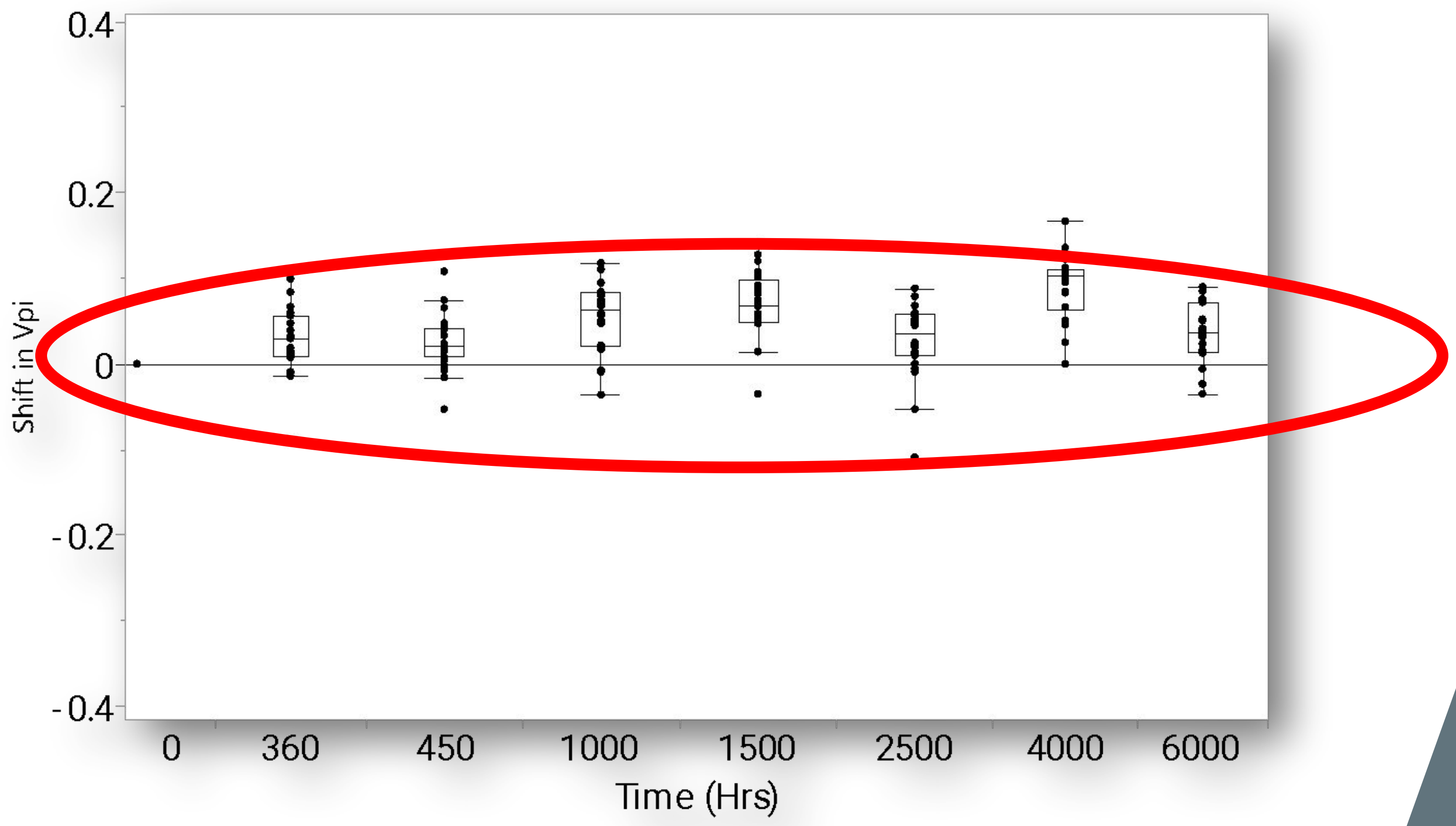
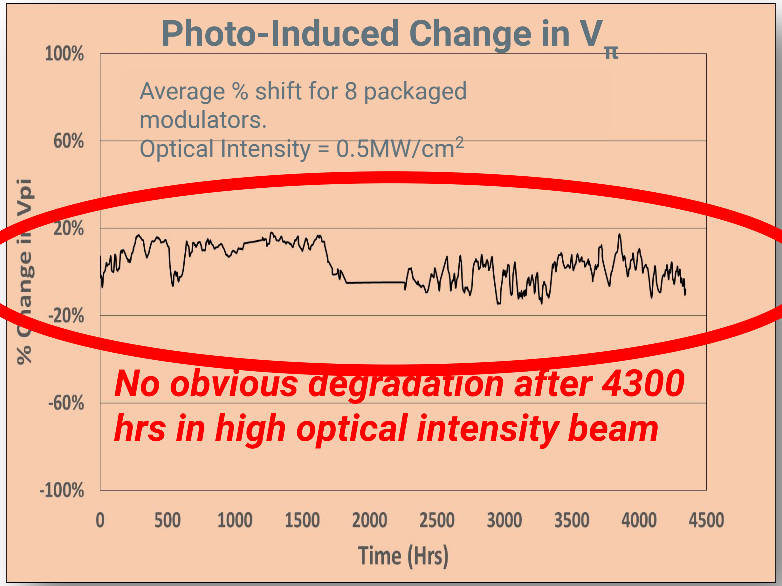
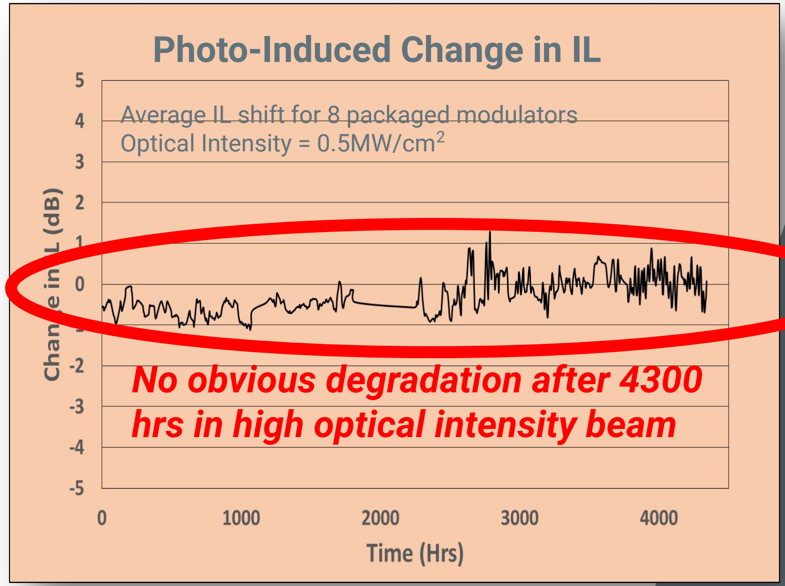


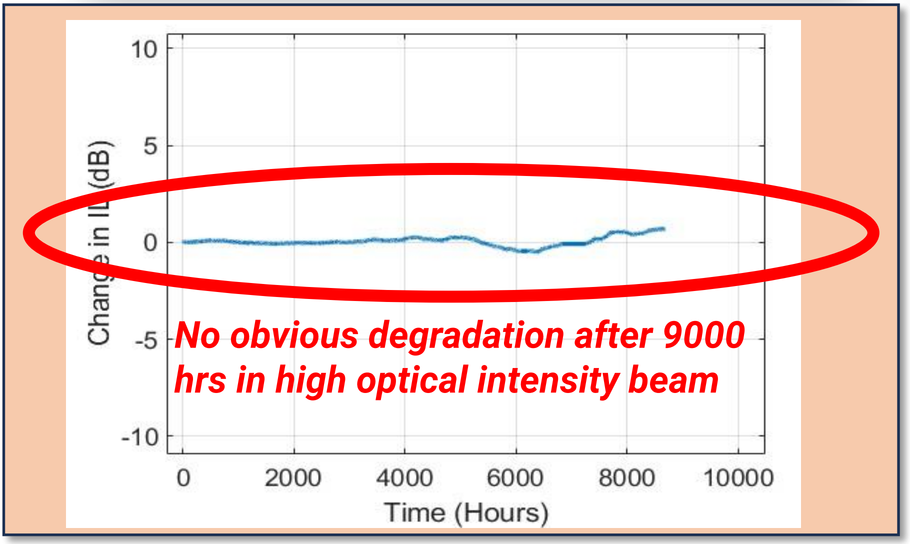
- The V_π on 20 modulators is stable over 6000hrs.
- The average shift over ~ 6000hours is 1.2% and it is within the margin of error of the test setup.

Modulator V_π stable after 6000 hrs

Photostability vs Voltage and Insertion Loss







Long and short-term photostability does not seem to be an issue with LWLG EO chromophores when protected from O_2

LIGHTWAVELOGIC


Our business model is innovative…

Implementing a new technology platform…

LIGHTWAVELOGIC®

Licensing model provides inherent scalability

Technology	3 Prong Strategy	Goals
Chromophore & Polymer Matrix IP	Product Sales	**Make polymers ubiquitous (just like OLEDs)**
Devices & PIC Architecture IP	Patent Licensing*	**Have device/PIC teams use EO polymers in their device/PIC designs**
Fabrication & Processing	Technology Transfer	**Supply polymer modulator OSAs for transceivers**
High Speed Package & Assembly Design IP		**Have foundries use EO polymers in PIC PDKs**
		Polymers in broad market verticals

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

Heterogeneous integration takeaways…

- Our heterogeneous polymer/silicon platform is poised to *become ubiquitous* (just like OLED polymer material)

- We are open *to license our material,* do technology transfer, and to leverage your position in the market-place…

- EO polymers continue to show technical progress with *polymer reliability and stability…200G lanes* and performance head-room to go 400G lanes and more…

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LIGHTWAVE LOGIC®
Faster by Design

Thank you for listening

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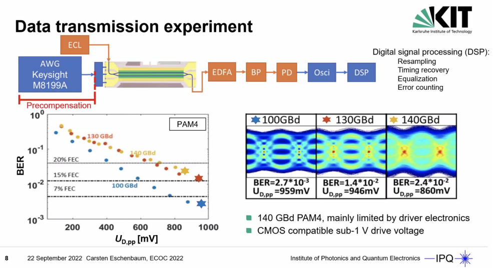
BACK-UP

3rd party verification…

3rd party use of Perkinamine® LWLG polymers

LIGHTWAVELOGIC®

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



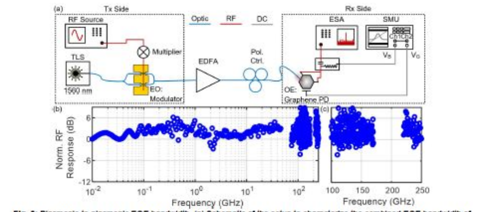
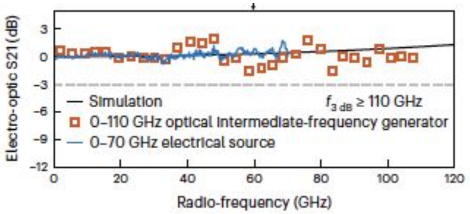
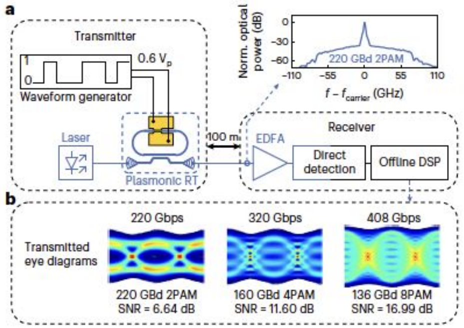


Fig. 3: Plasmonic-to-plasmonic EOE bandwidth. (a) Schematic of the setup to characterize the combined EOE bandwidth of the plasmonic racetrack modulator linked to the metamaterial graphene PD. (b) Measured normalized RF response of the system showing an EOE bandwidth of 250 GHz and (c) the response visualized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





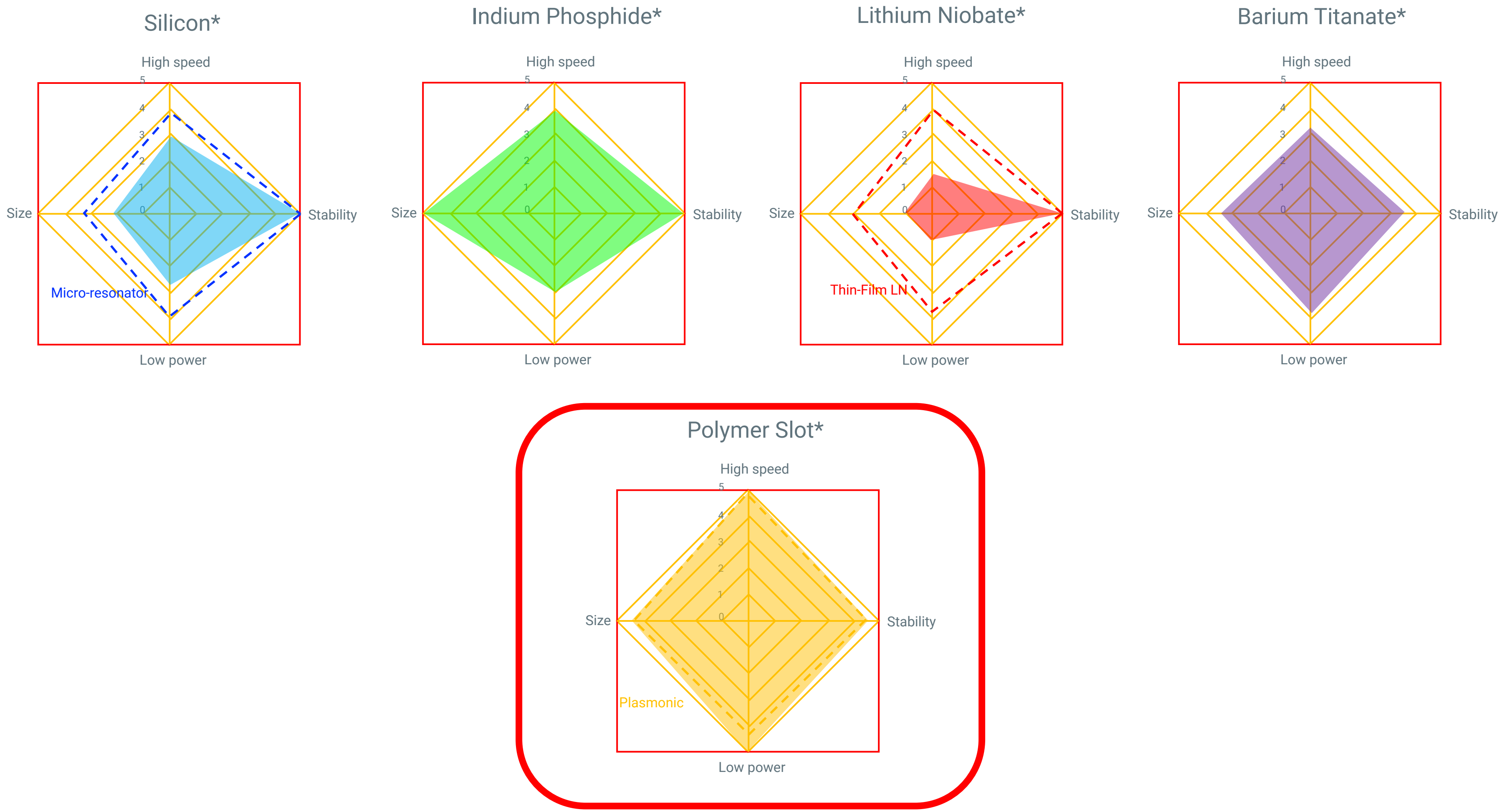
Sources: KIT, SilOriX, EU Horizon 2020, ETH Zurich, Polariton, CAU University Kiel (post deadline paper published at ECOC2022 using LWLG EO polymers)*

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

EO polymers are competitive with semiconductor modulators…

Polymer attributes are impressive…

LIGHTWAVELOGIC®



Technology spider chart □ polymers have strong coverage □ excellent performance

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

How important is glass transition temperature (T_g)?

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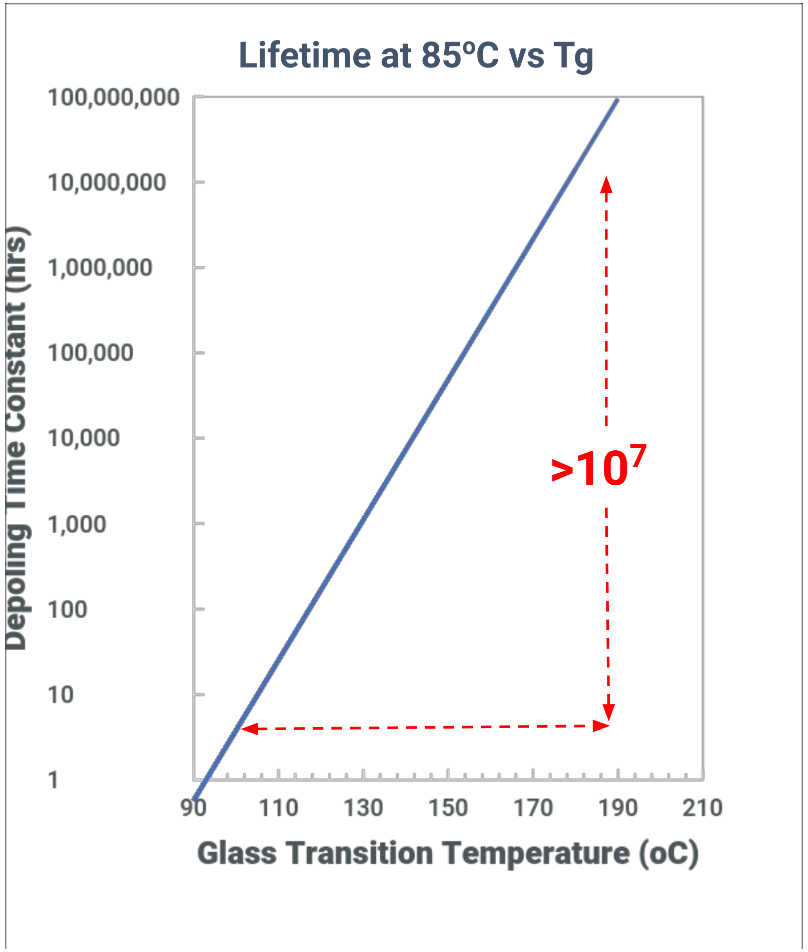
The thermal lifetime of an EO-polymer against thermally induced depoling material at 85°C will **increase** with increasing T_g

The lifetime at 85°C for a polymer with **T_g =180°C is >10^7 times greater than** that lifetime for one with **T_g= 100°C**



After Organic Electro-Optics and Photonics by Dalton, Gunter, Jazbinesek, Kwon and Sullivan

Design for Reliability: Increasing Tg means much higher lifetime in electro-optic materials