LIGHTWAVE LOGIC®

Faster by Design

Positioning electro-optic polymer modulators as an optical engine to extend data rate and low power performance for optical networking

Michael Lebby, CEO

Lightwave Logic (NASDAQ:LWLG)

Safe harbor

LIGHTWAVELOGIC®

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.

Outline

- Takeaways
- Hybrid PICs
- EO polymer performance
- Foundry partnering
- Going fast…
- Summary

4 takeaways...

Takeaways

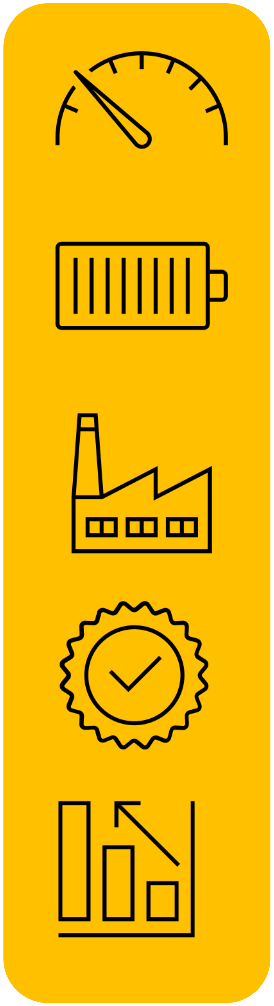
LIGHTWAVELOGIC®

- We have unique polymers…
- Our technology is ultra-fast with stable materials…
- We are positioned to scale polymers to become ubiquitous…
- Polymers are foundry and pluggable TxRx 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 using hybrids

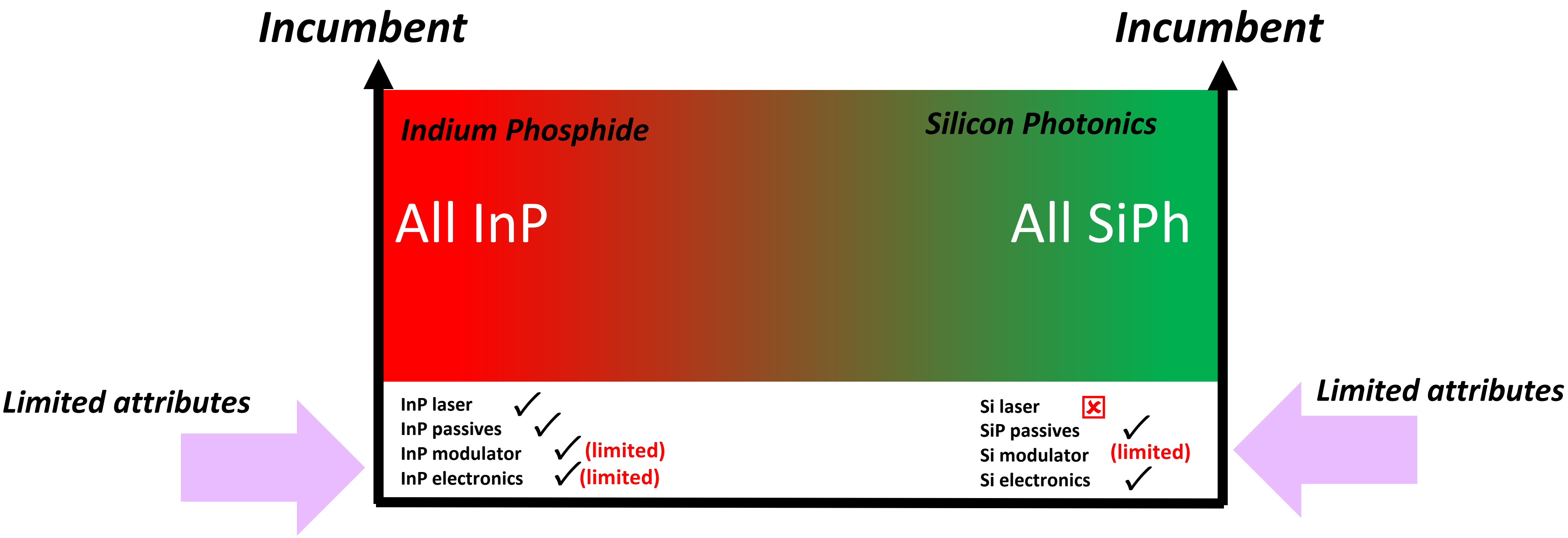


Our commercial grade Perkinamine™ (Pk™) Polymers are unique in their properties

Source: Lightwave Logic (LWLG)

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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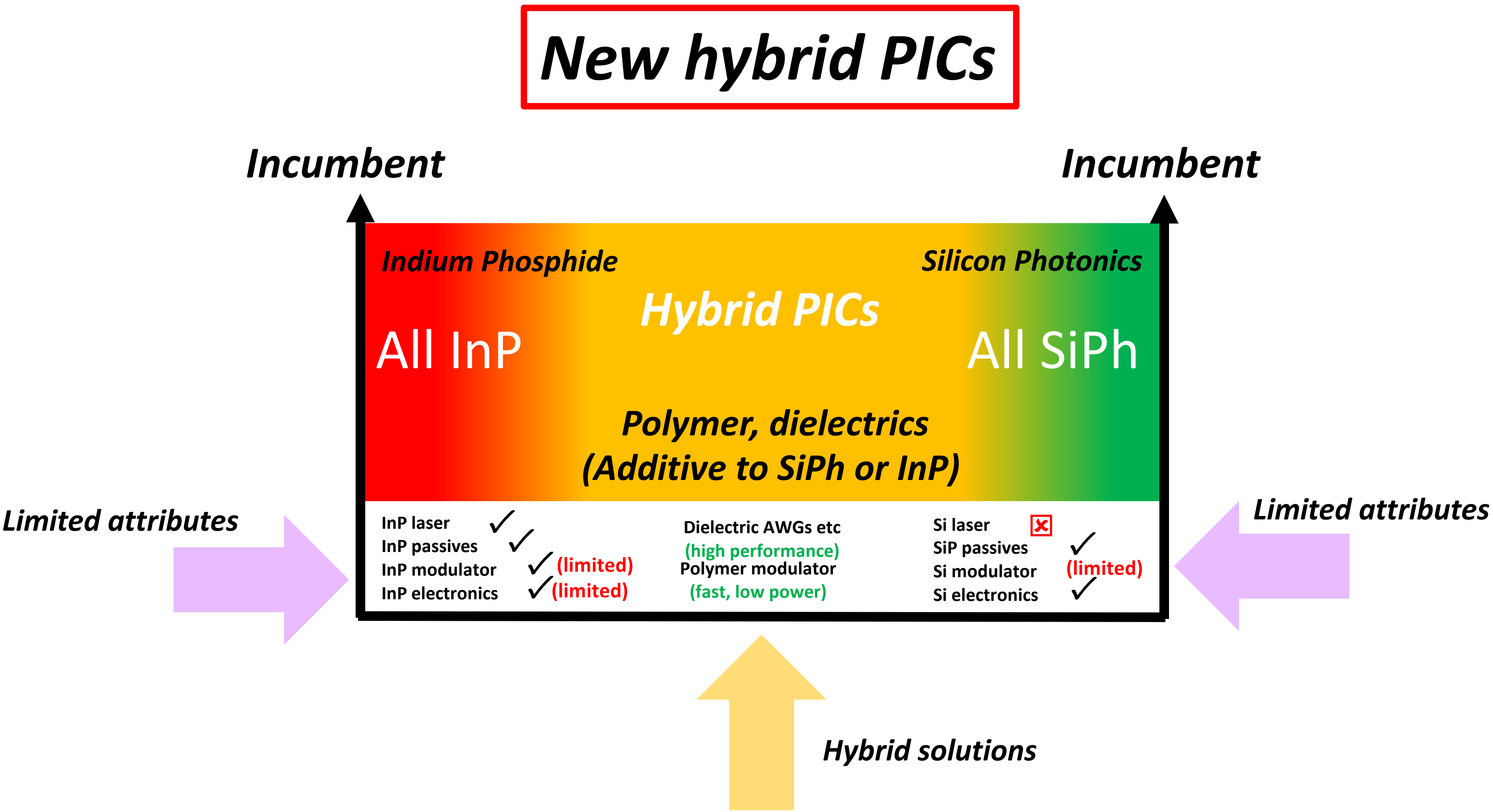

Hybrid PICs can boost performance of PICs

Source: LWLG

EO Polymer material performance

Commercial performance by Pk™ series

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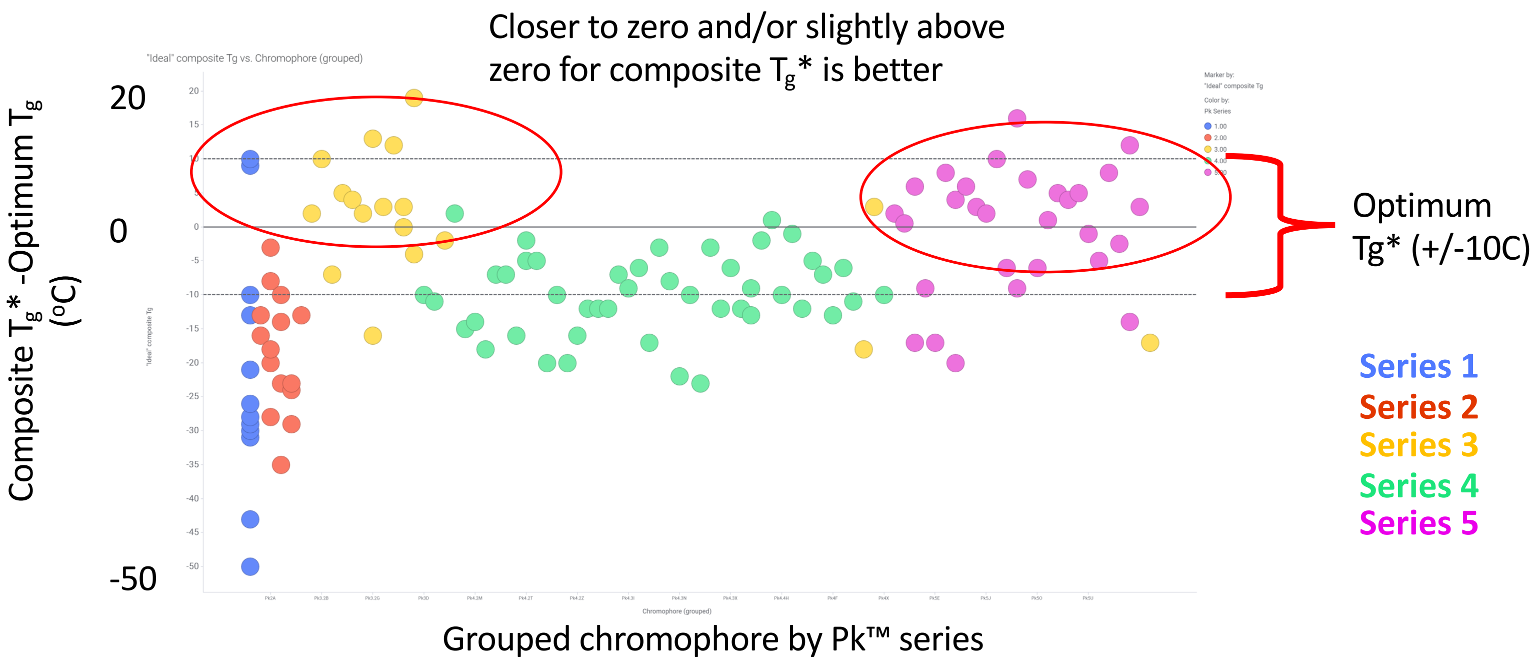
- T_g-Ideal T_g* vs Perkinamine™ chromophore (Pk™) Series



*Optimum Tg (glass transition temperature) is >> maximum operating temperature (but not so high that thermal disorder degrades poling efficiency)

Results show that Pk™ series 3 and 5 represent significant improvement

Source: LWLG

Maximizing Commercial FOM 1 for optical performance

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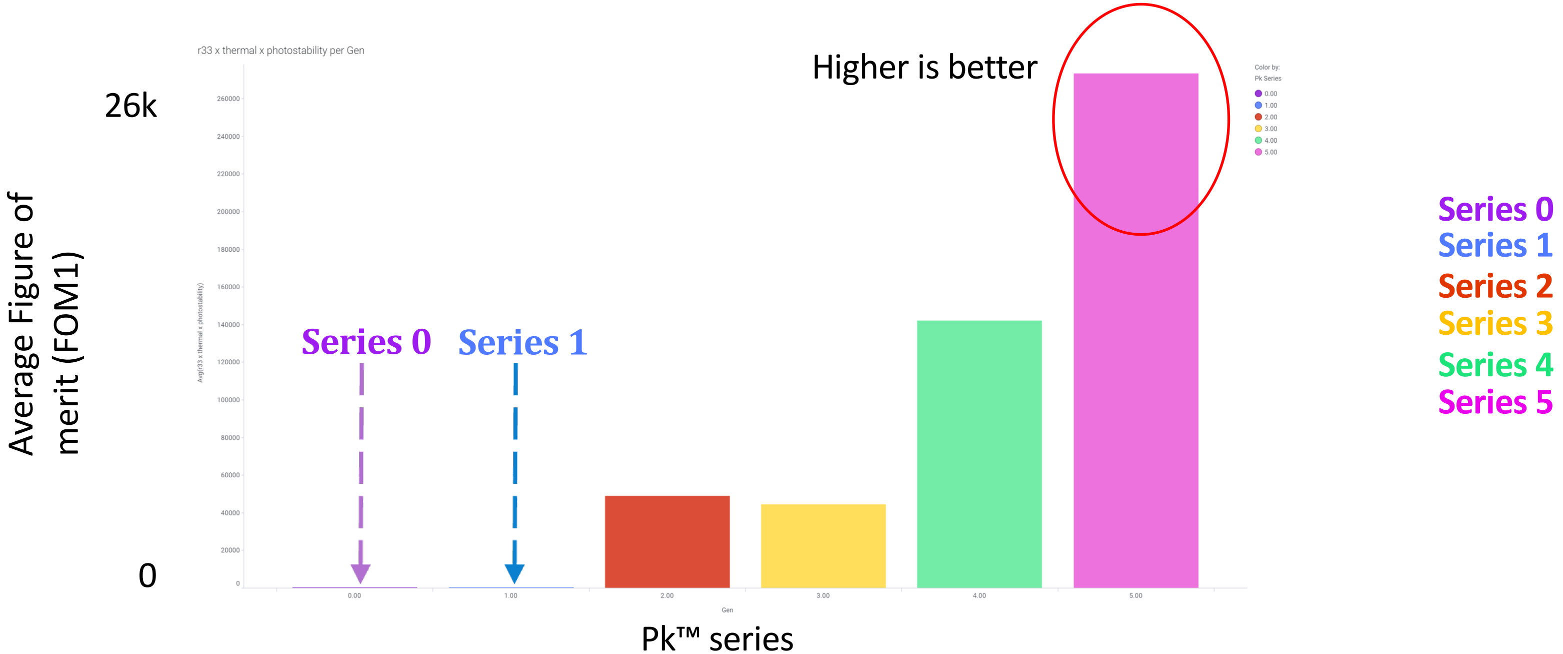
- Average FOM 1 (=r_{33} x thermal stability x photostability) versus Pk™ series



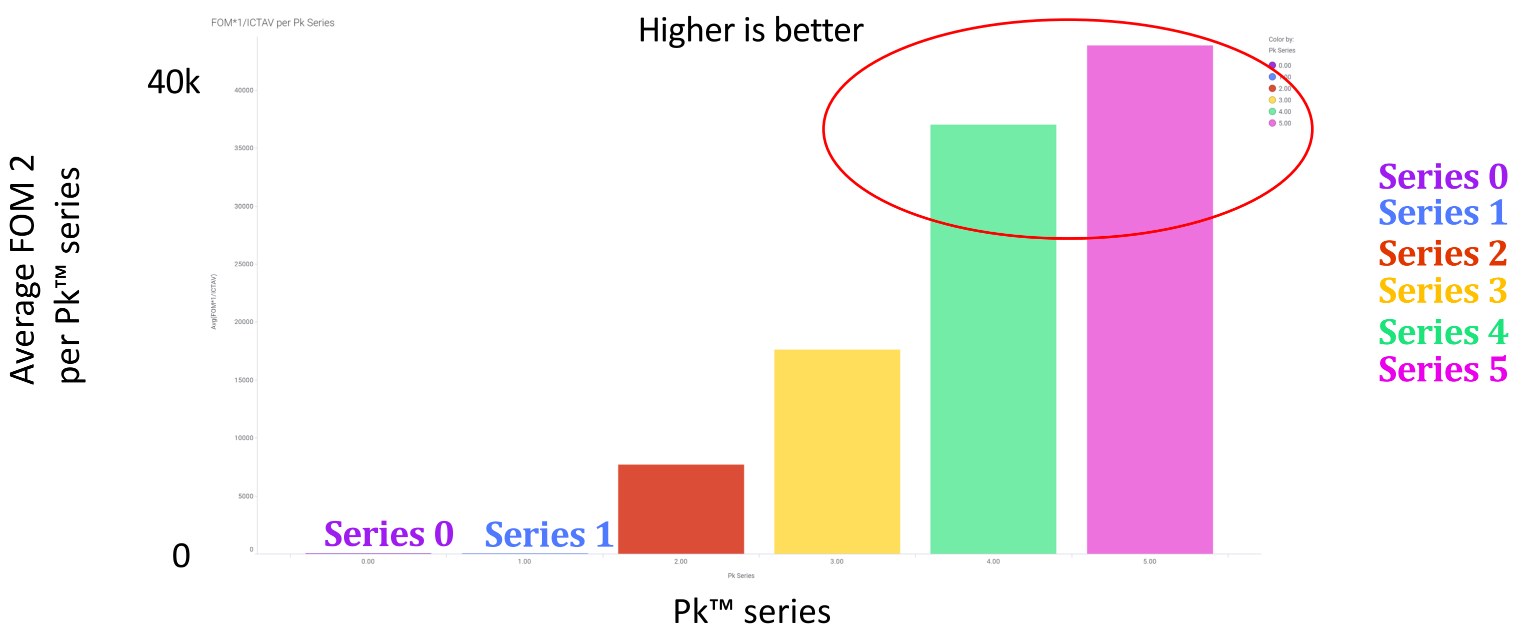
- This Figure of Merit reflects the need for both high electro-optic activity and high stability for reliability

Commercial Perkinamine™ series 5 outperforms all previous chromophore designs significantly (high r33, thermal/photo stability)

Source: LWLG

Commercial Figure of Merit 2 (FOM 2) by Pk™ series

- Commercial FOM 2 (=FOM 1 /abs[T_g-Optimum T_g]) includes in addition need for high T_g



*Optimum Tg (glass transition temperature) is >> maximum operating temperature (but not so high that thermal disorder degrades poling efficiency)

Pk™ series 5 more advanced and performs better compared to previous EO materials

Source: LWLG

Commercial level thermal stability

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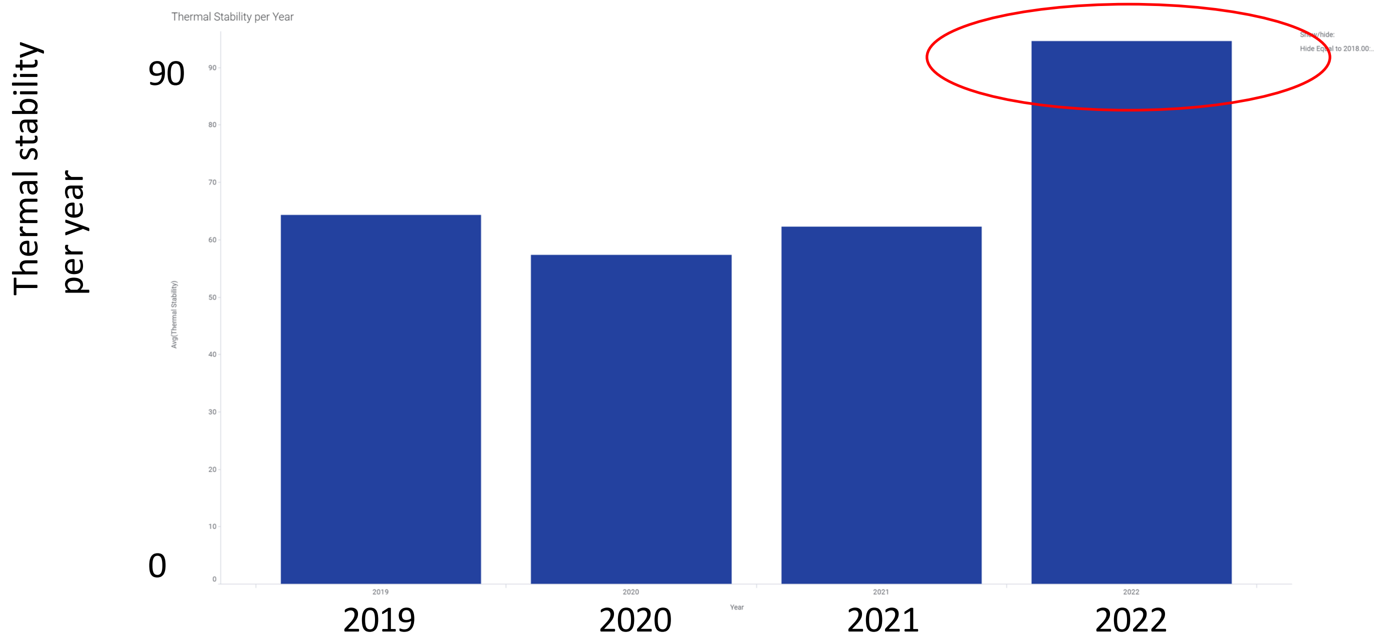
- Average thermal stability per year

Higher is better
Gen 5 performs best



Thermal stability improvement each year

Source: LWLG

Perkinamine™ thermal stability

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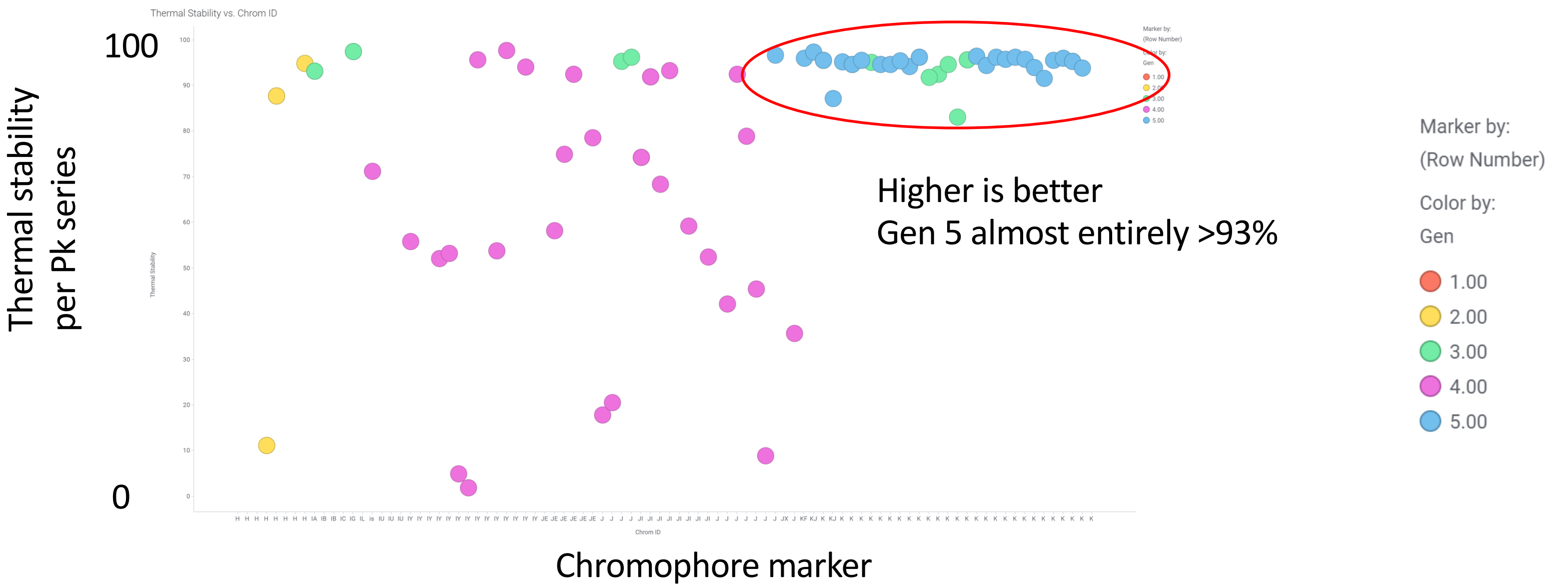
- Chromophore marker showing improvement in thermal stability



Thermal stability improvement significant with each Pk™ generation

Source: LWLG

Foundry partnering

Foundry compatibility for PIC modulators

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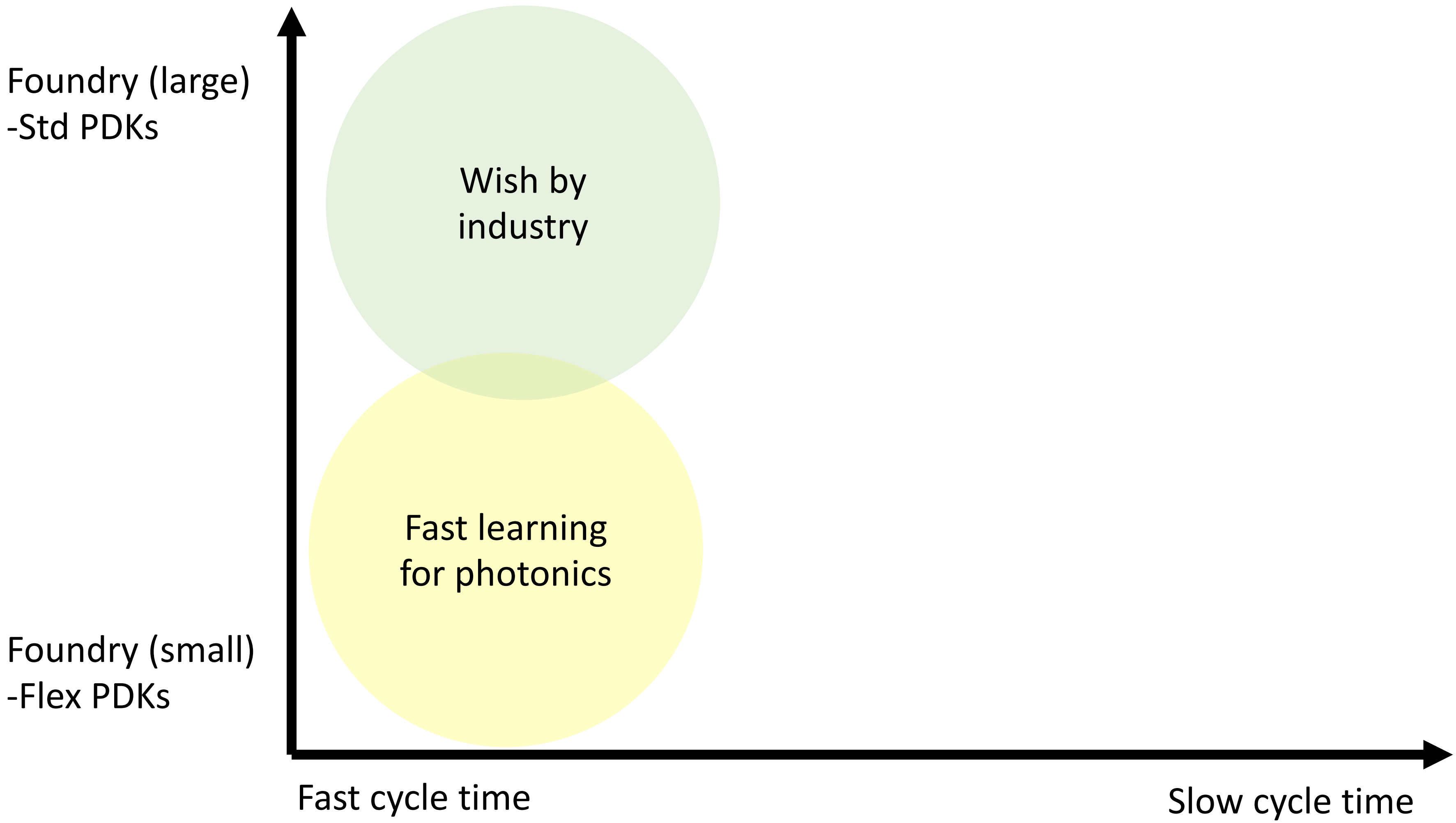
New technology	Foundry compatibility	Performance head room
Polymer (modulators)	Silicon, III-V	>100GHz many generations
Polymer plasmonic (modulators)	Silicon, III-V	>250GHz many generations
Polymer plasmonic rings (modulators)	Silicon, IIII-V	>250GHz many generations
Barium Titanate (modulators)	Silicon (?)	~70GHz (?)
Indium Phosphide (EAMs)	InP, Silicon with bonding	~ <70GHz
Silicon modulators	Silicon	~ <30-40GHz (doping)
Silicon Rings (modulators)	Silicon	~ <50-60GHz (thermal)
Thin Film Lithium Niobate (modulators)	Lithium Niobate Silicon ?	~ <70GHz (this generation)

Hybrid polymer enables economies of scale headroom

Source: LWLG

Photonics foundry experience…



Photonics industry wants fast iterative learning for silicon photonics

Source: LWLG

Foundries have standard metrics

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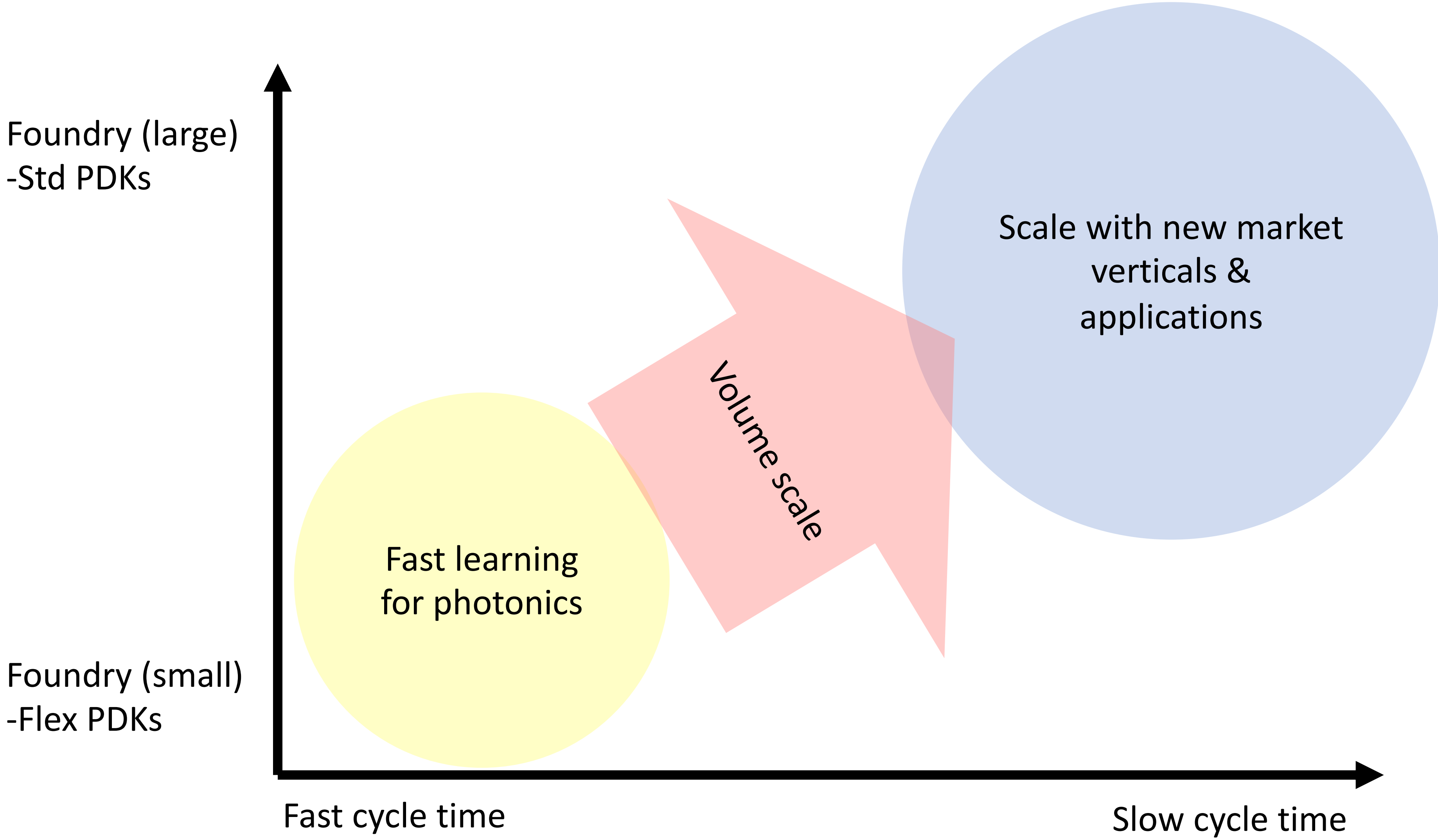

Foundries want silicon photonics to increase wafer throughput

Source: LWLG

Route to PDK acceptance

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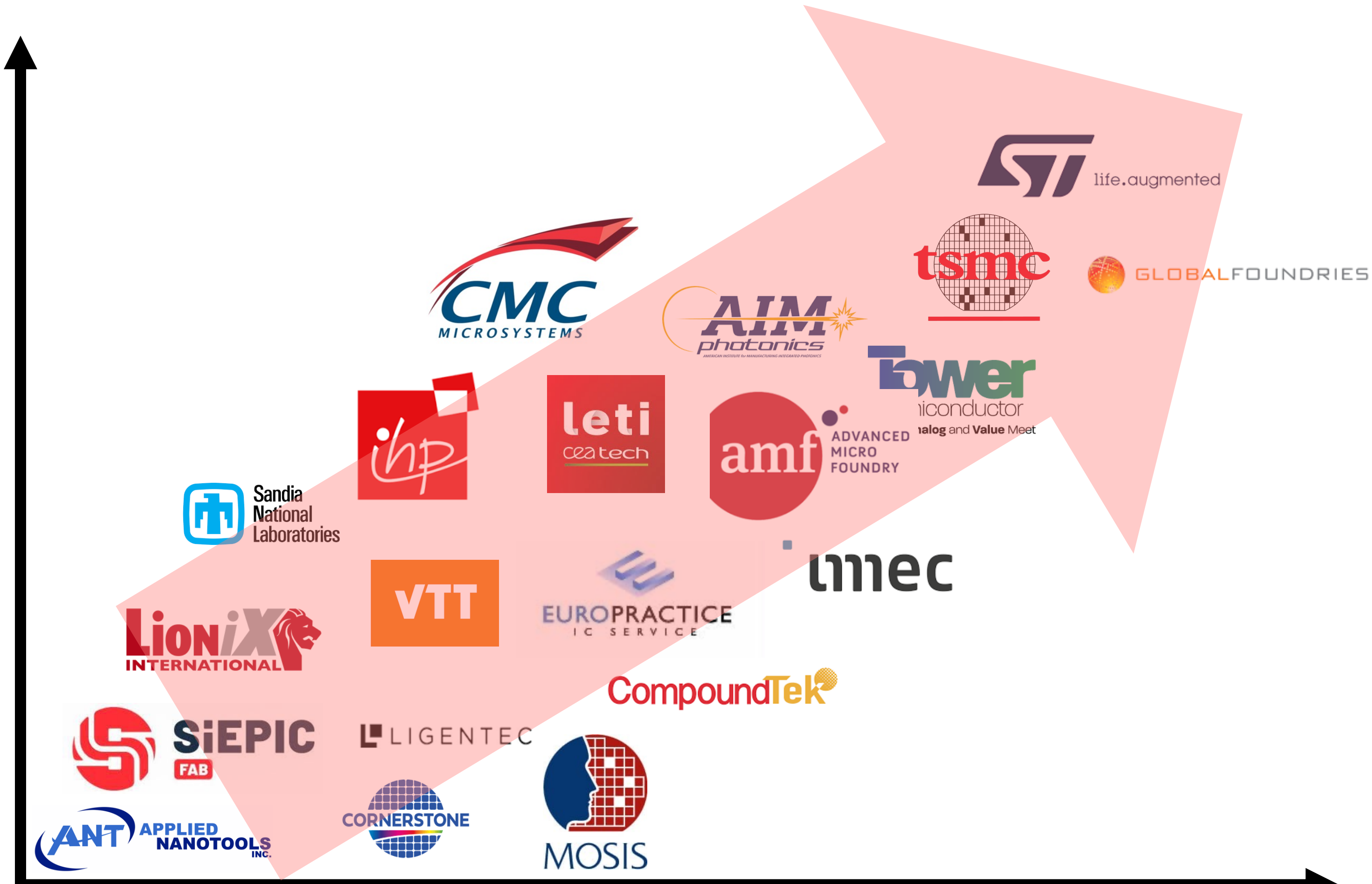
Foundry (large)
-Std PDKs



Foundry (small)
-Flex PDKs

Fast cycle time

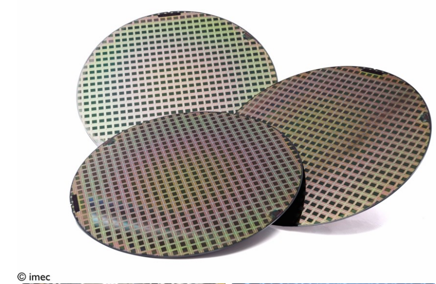
Slow cycle time

Foundries want silicon photonics to increase wafer throughput

Source: LWLG

Partnering for success

- Partnering with foundries, packaging partners and module/transceiver partners to position LWLG for future high-volume production
- Partnering to integrate with 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

Polymer Slot™ device structure

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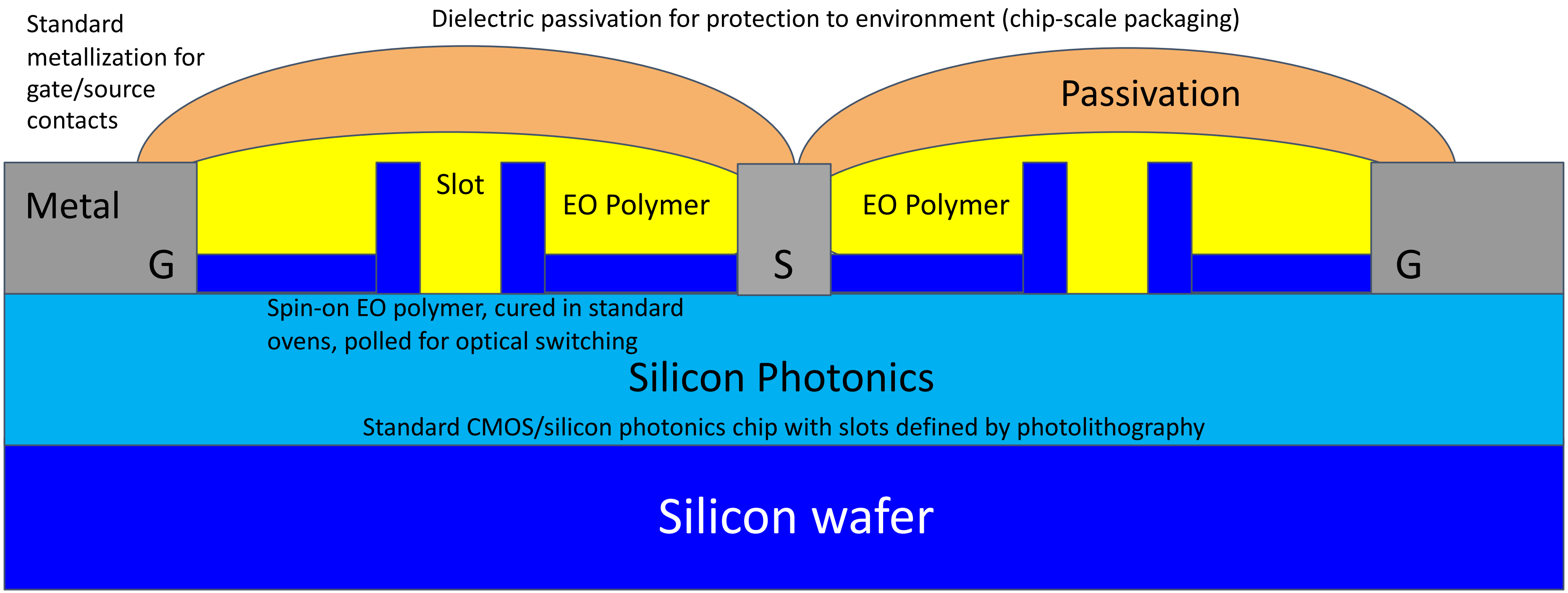
Standardized, consistent poling process with extremely high yields



Standard silicon fabrication processes; standard silicon tools

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

Foundry fabrication with PDK

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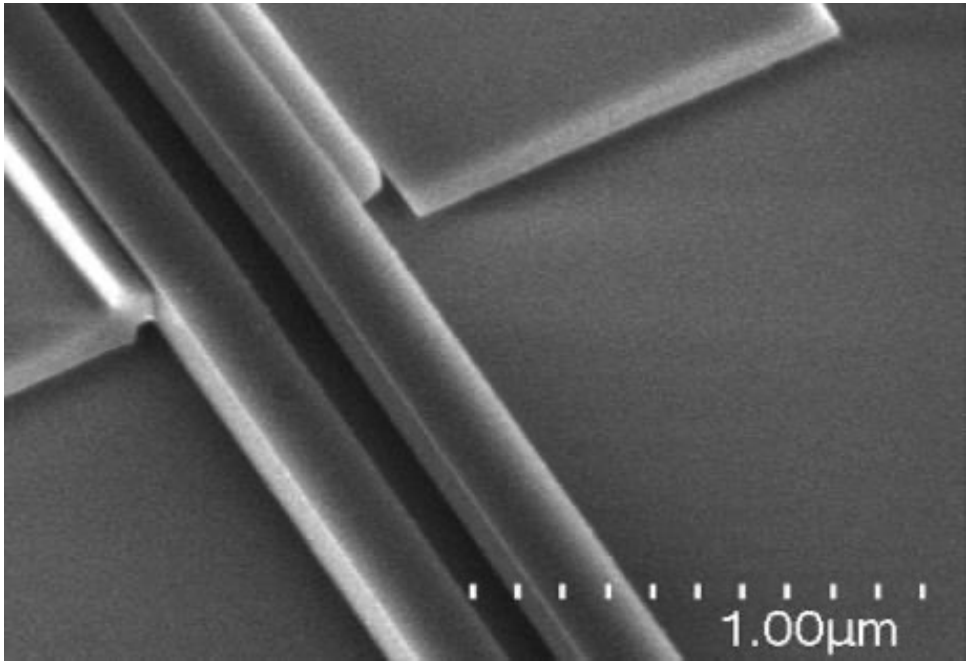

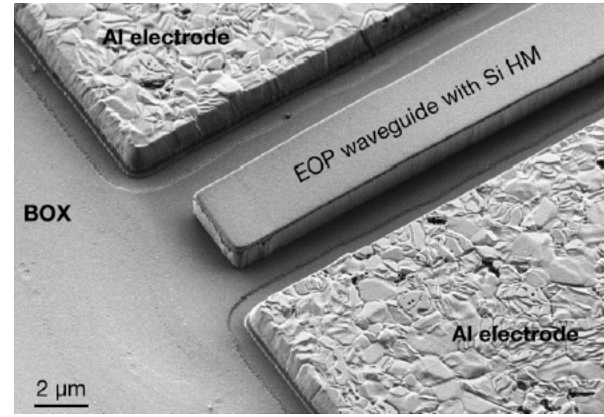

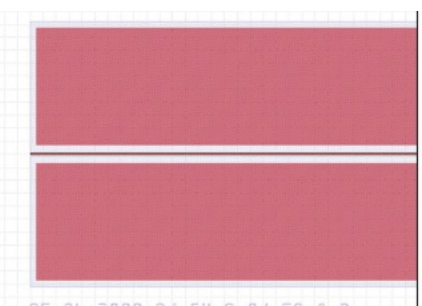

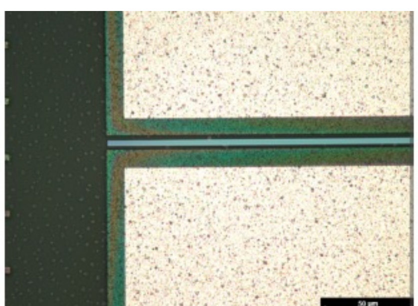

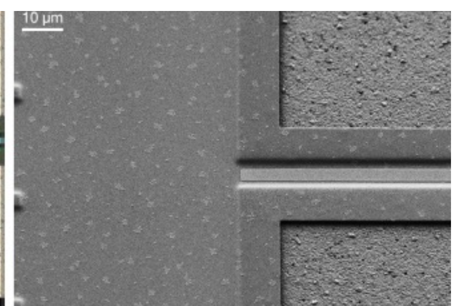

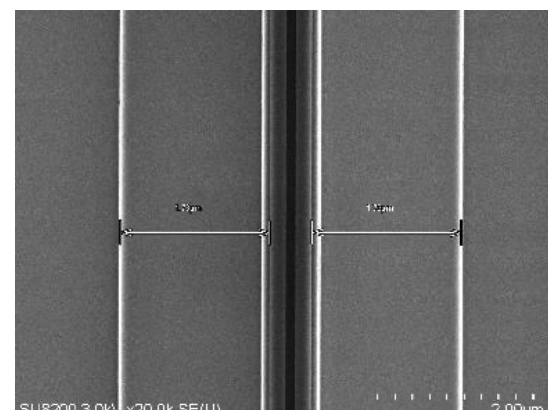

Standard silicon fabrication components…

Source: Lightwave Logic (LWLG)


Going fast…

EO polymers break through the *speed wall*

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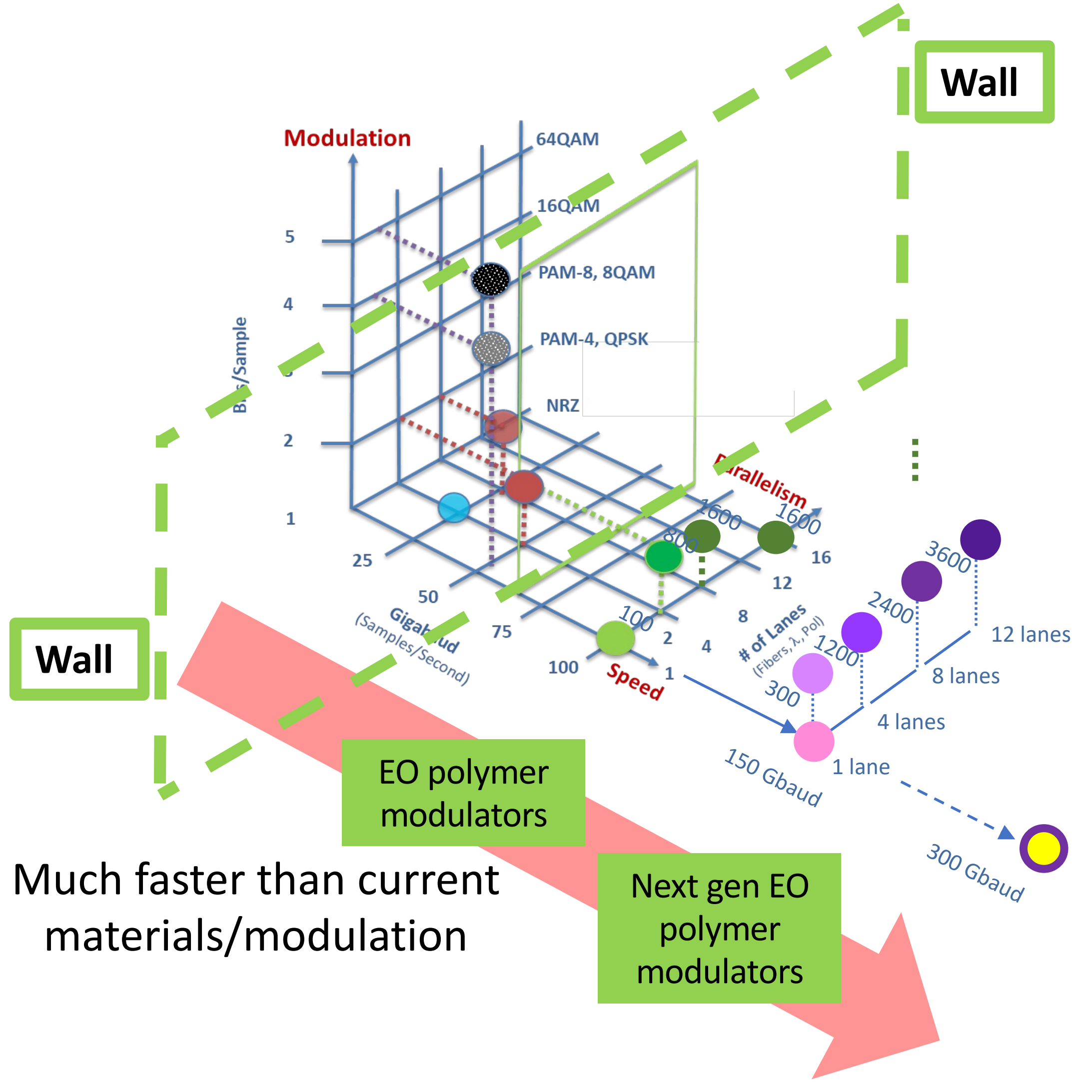

Much faster than current materials/modulation

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

- 300Gbps = 300Gbaud, NRZ, 1 lane

Ultra-fast speed…

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

Polymer modulator performance

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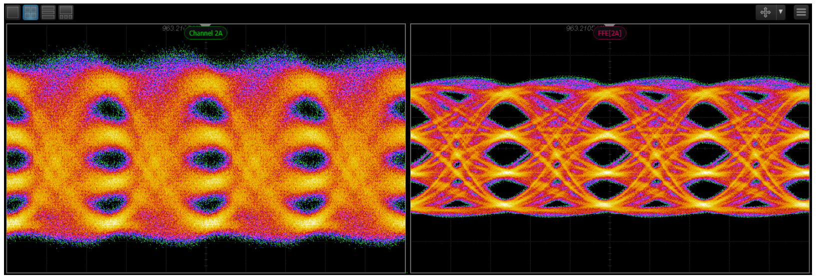
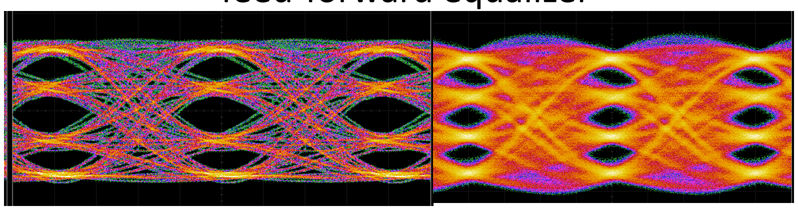
Raw optical measurement | With simulated feed-forward equalizer



40 Gbaud PAM4
80 Gbps
2 V drive

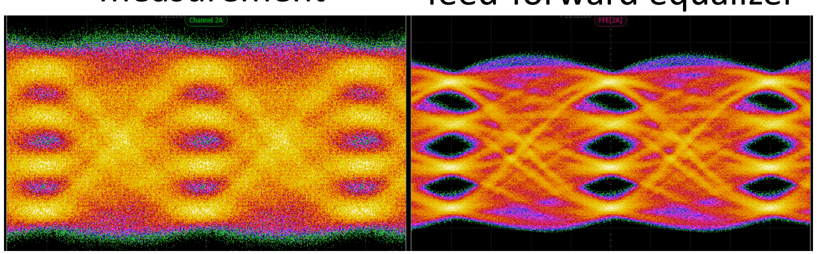
With simulated feed-forward equalizer



30 Gbaud PAM4
60 Gb/s
2 V drive

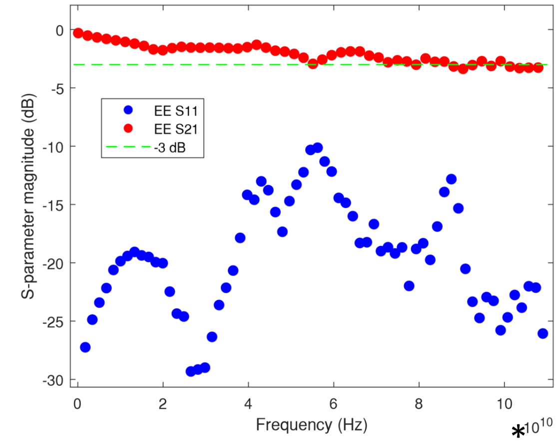
50 Gbaud PAM4
100 Gb/s
2 V drive

Raw optical measurement | With simulated feed-forward equalizer

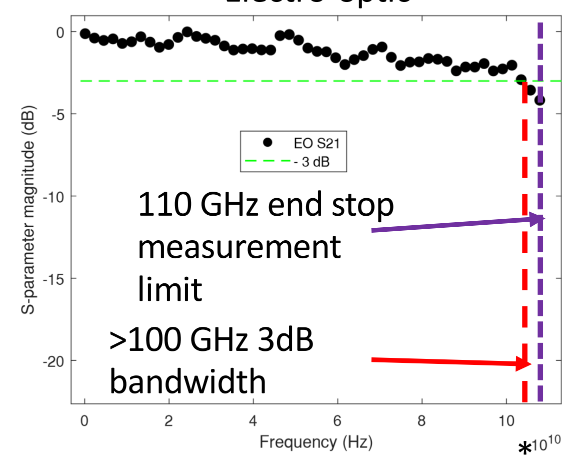


50 Gbaud PAM4
100 Gb/s
2 V drive

Electrical



Electro-optic



*

Recent high-frequency S-parameter data from polymer modulators

Clean PAM4 eyes at 80Gbps with EO S21 >100GHz 3dB bandwidth

Source: LWLG

Summary

Takeaways

LIGHTWAVELOGIC®

- We have *unique* polymers…
- Our technology is *ultra-fast with stable materials*…
- We are positioned to scale polymers to become *ubiquitous…*
- Polymers are *foundry and pluggable TxRx compatible…*

Company address

369 Inverness Parkway, Suite 350
Englewood, CO 80112

lightwavelogic.com

Thank you!

Ultra..., Unique, and Ubiquitous...


Back-up

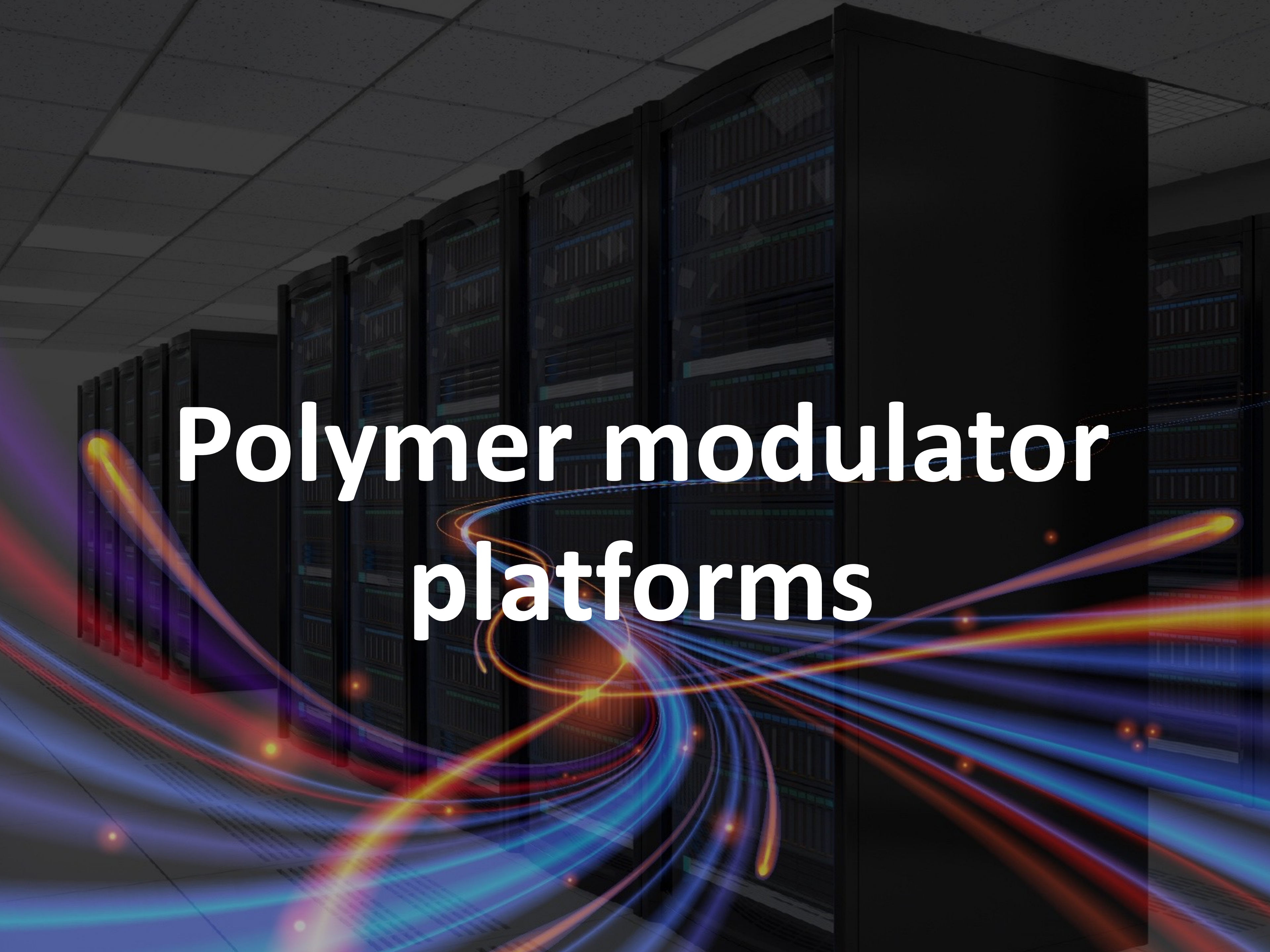

We are excited…

NASDAQ 1yr Anniversary

LIGHTWAVELOGIC®

1st Sept 2022: 1yr on NASDAQ

Source: NASDAQ


Polymer modulator
platforms

Natural integration with big foundries

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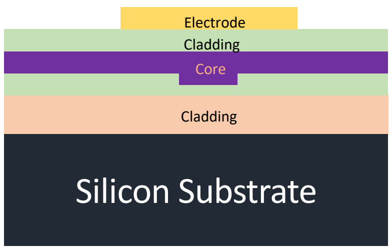
Additive to semiconductor platforms (SiPh, InP…) to enhance performance

Polymer Stack™

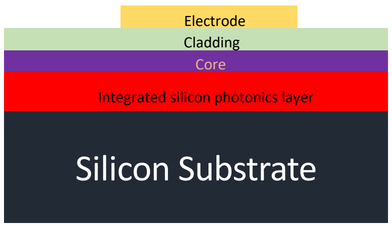


Classic!

Polymer stack modulator

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

Polymer Plus™

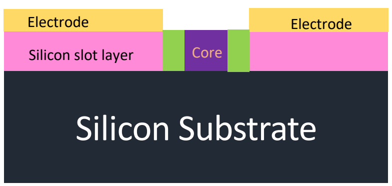


Additive!

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…

World class results (using EO polymer material)

World record EO polymer results

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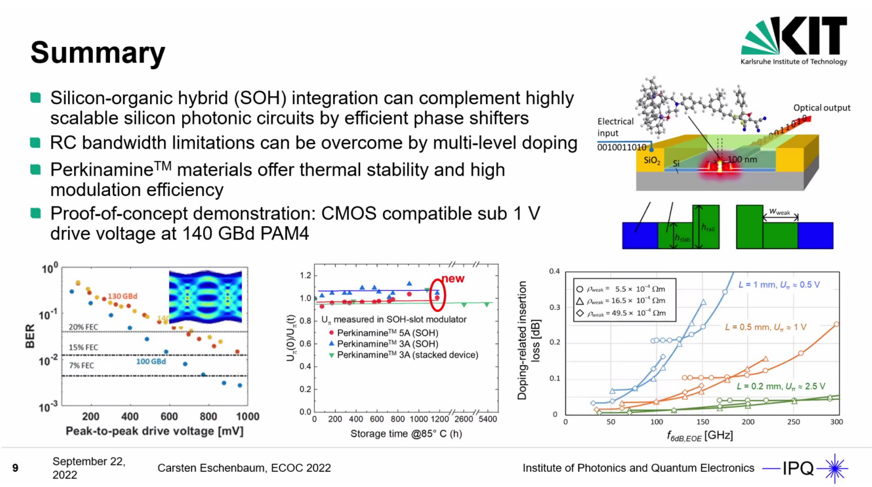
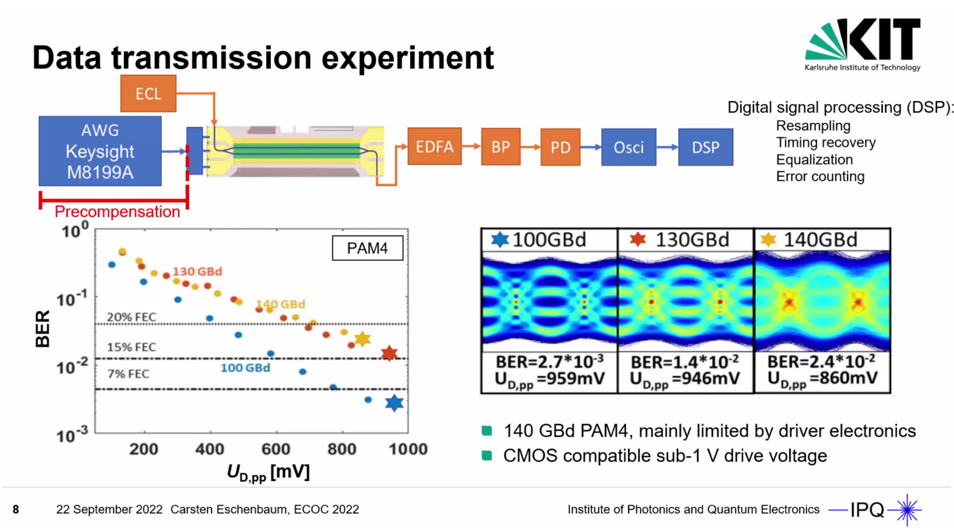


- Paper: 'Thermally stable SOH MZ modulator for 140Gbd PAM4 transmission with sub-1V drive signals
- Focus on stability

- World record performance electro-optic polymer silicon slot modulators
- Competitive low BER using FEC limits as per traffic rates



Silicon based electro-optic polymers and silicon photonics demonstrate world class speed of operation

Sources: KIT, SilOriX, EU Horizon 2020, and post deadline paper published at ECOC2022 using LWLG EO polymers

Industry 3rd party review (ECOC 2022)

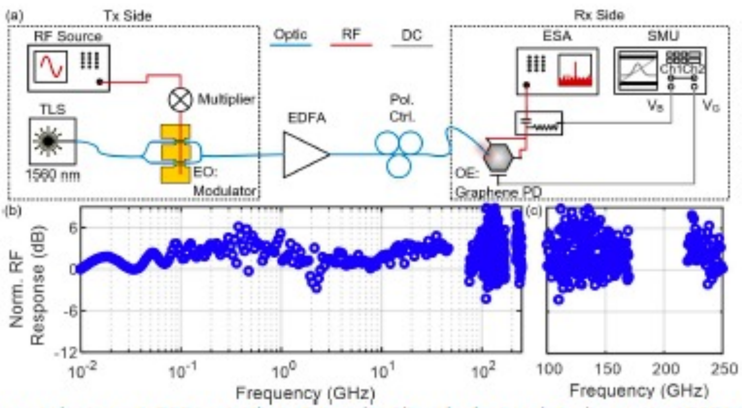


Fig. 3: Plasmonic-to-plasmonic EOE bandwidth. (a) Schematic of the setup to characterize the combined EOE bandwidth of the plasmonic racetrack modulator linked to the metamaterial graphene PD. (b) Measured normalized RF response of the system showing an EOE bandwidth of 250 GHz and (c) the response visualized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

- Paper: '>500GHz bandwidth graphene PD enabling highest-capacity plasmonic-to-plasmonic' links

- World record performance electro-optic polymer plasmonic slot modulators working in a fully plasmonic link using LWLG EO-polymer material

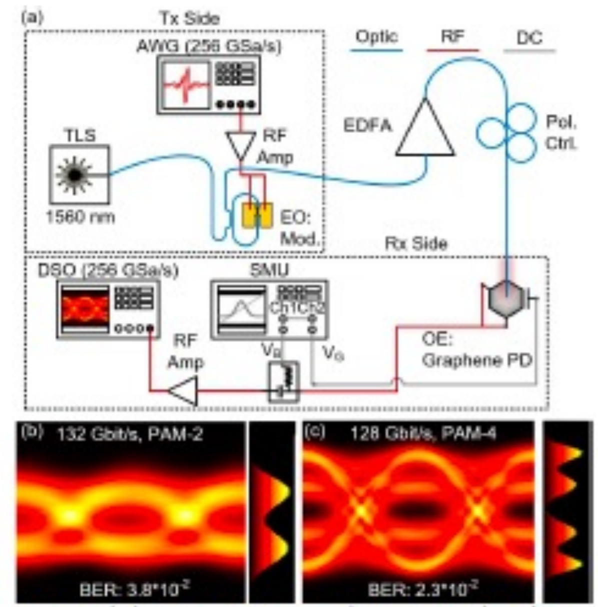


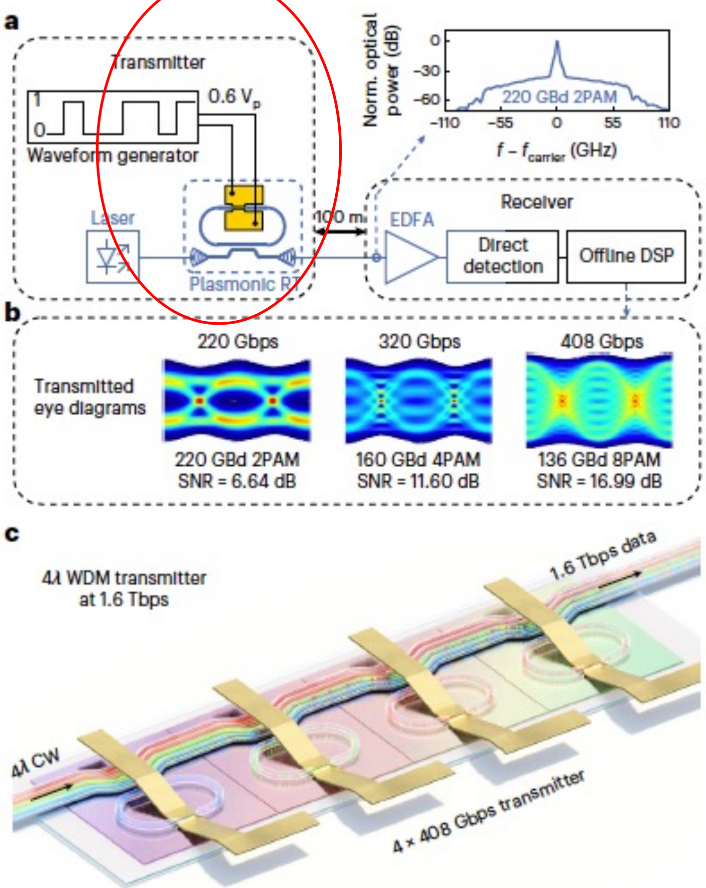
Fig. 4: Data transmission experiments. (a) Schematic of the used setup with the plasmonic racetrack modulator on the Tx side and the metamaterial GPD on the Rx side. (b,c) Optical eye diagram after offline DPS for 132 Gbit/s PAM-2 and 128 Gbit/s PAM-4 respectively.

Electro-optic polymers outperform silicon modulators

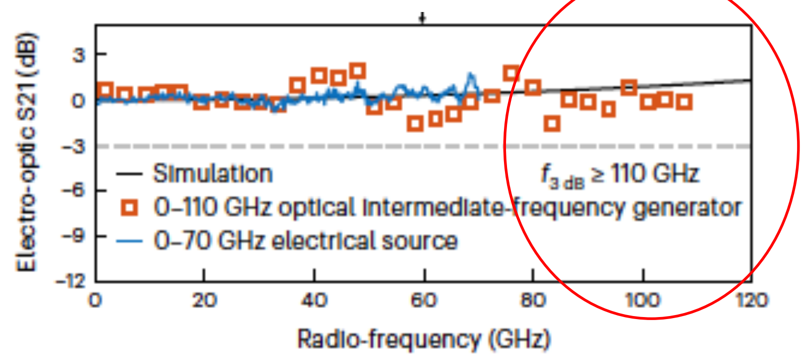
Sources: ETH Zurich, Polariton, CAU University Kiel, EU Horizon 2020

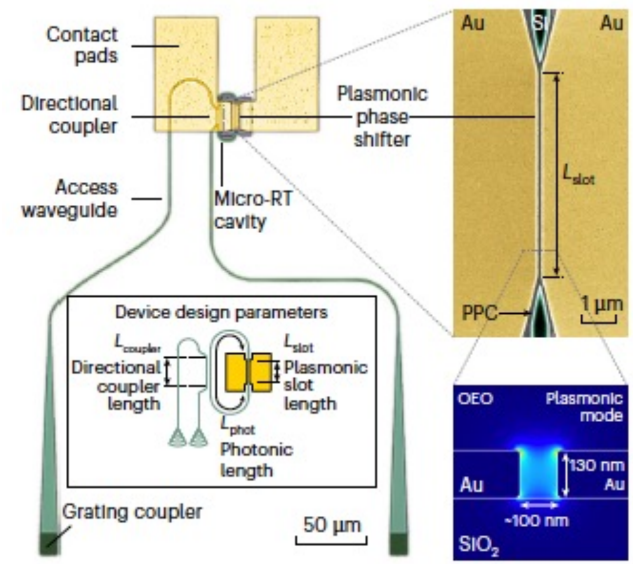
EO polymer plasmonic ring resonators

0.6V and EO polymer material from LWLG



>110GHz EO dB bandwidth





https://doi.org/10.1038/s41566-023-01161-9

Electro-optic polymers plasmonic ring resonators achieve >408Gbps with 0.6V and EP polymer material

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

EO polymer plasmonic ring resonators

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- World record performance of electro-optic polymer plasmonic ring resonator modulators compared to competitive ring resonators in silicon & TFLN

Table 1 | Literature overview of geometric, resonance and data transmission properties of published resonant modulators achieving >60 Gbps

Type	Reference	Circumference (μm)	FSR (nm)	Q factor	$V_{\pi}L$ (V μm)	Electrical tuning (pm V^{-1})	Bandwidth (GHz)	Modulation format	Line rate (Gbps)	Driving voltage (V_p)
Plasmonic MRM	15	6	115	30	*	2,750	>115	2PAM	72	3.3
Si MRM	52	31	13	4,800	3,700	33	45	2PAM	60	0.8
								4PAM	100	1.25
Si MRM	53	31	20	3,000	*	33	55	4PAM	160	1.2
Si RT	54	60	7	5,600	8,000	26	79	2PAM	120	*
								4PAM	200	*
Si RT	24	60	7	5,600	8,000	26	67	DMT	301	*
Si MRM	55	38	11	4,200	5,300	*	77	2PAM	128	0.4
								4PAM	192	0.8
Si MRM	25	25	16	4,000	5,300	*	62	4PAM	240	0.9
TFLN Bragg	56	*	*	200,000	*	15	60	2PAM	100	0.9
								4PAM	100	0.9
Plasmonic RT	This work	~90	7	~700	150	>178	176	2PAM	220	0.6
								4PAM	320	0.6
								8PAM	408	0.6

The plasmonic RTs presented in this work achieve 1.7 times improved data transmission speed (for intensity-modulated/PAM formats) with low 0.6 V_p driving voltage and a 2.2 times increased bandwidth over Si MRMs. TFLN, thin-film lithium niobate. Values denoted with * are not available.

https://doi.org/10.1038/s41566-023-01161-9

Electro-optic polymers plasmonic ring resonators outperform silicon rings…

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