LIGHTWAVE LOGIC™

OTCQB: LWLG

# ECOC Market Focus:

## "Polymer modulators with >50GHz performance for power consumption reduction at 400, 800, and 1600 Gbaud aggregated datarates"


Michael Lebby

CEO Lightwave Logic Inc



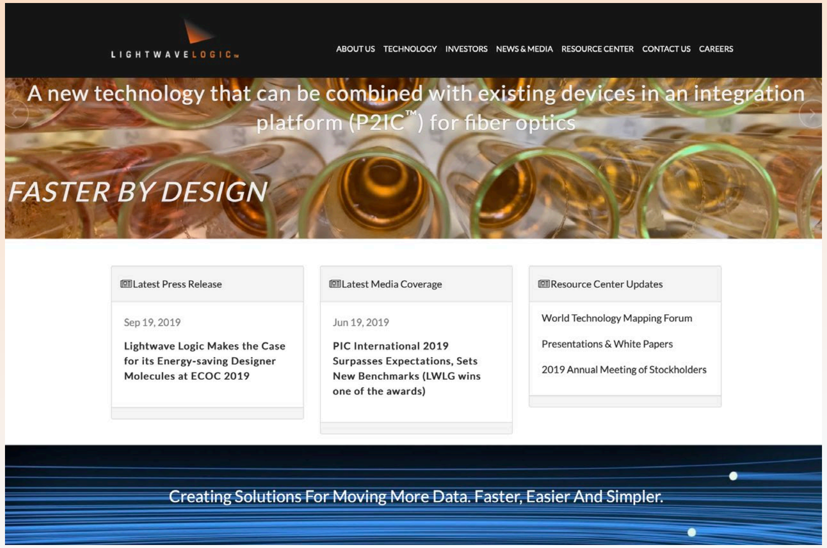

*Faster by Design*

# 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.

# Slide presentation will be posted at website




www.lightwavelogic.com

Sit back…relax…

# Agenda



- Key trends
- Target Markets: large & facing a growing gap
  - Market environment
  - Market gap
- Market technology opportunities
  - Faster devices,
  - Lower power,
  - Lower cost,
  - Robustness
- Roadmap update
- Summary

NB: These green bars give a summary of each slide

# Warning: Traffic jams on the information superhighway

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- Network cost and energy have become the new hot spot for data providers. This is the problem we seek to address.

Cost and energy are now focus areas…

 

# The problem is the speed limit of the optics…

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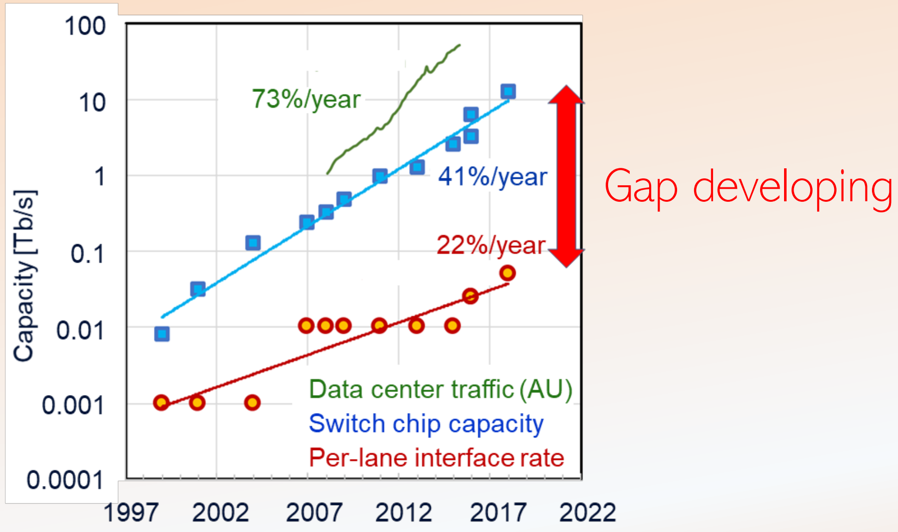
- The Network is falling behind the traffic growth




*Source: Peter Winzer, Nokia, "Scaling Optical Networking Capacity: Options and Solutions"*

Huge data volumes are enabled by **low cost and energy** for computation and storage. Thank you Moore's Law for semiconductors.

The big data pipes inside datacenters, between datacenters, and from datacenters to end-users are **fiber optic**. The problem? No Moore's Law for optics.

Radical innovation is needed…

# Delivering radical innovation…

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## Photonics must deliver solutions:

| Faster devices (100GHz+) | Lower Power (Low voltage) | Lower cost (Easy fab) | Robust (Stable) |
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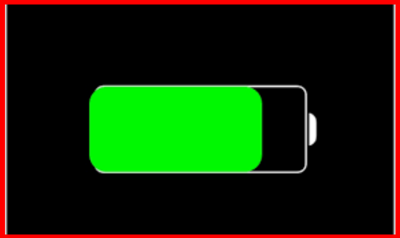
|  |  |  |  |

**To enable faster, lower power, lower cost internet…**

*Source: Lightwave Logic (LWLG)*

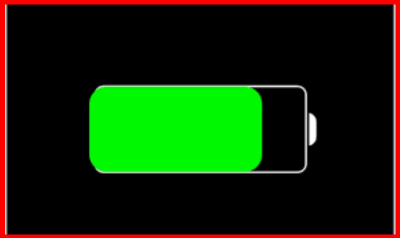
# Delivering radical innovation…



## Photonics must deliver solutions:

**Faster devices**
(100GHz+)


**Lower Power**
(Low voltage)



**Lower cost**
(Easy fab)

**Robust**
(Stable)

To enable faster, lower power, lower cost internet…

*Source: Lightwave Logic (LWLG)*

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# Faster devices…




*Fastest by Design*

# But the internet has been growing fine, so what's changed?

# Historical perspective

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

Easy

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

Tougher

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

Tougher

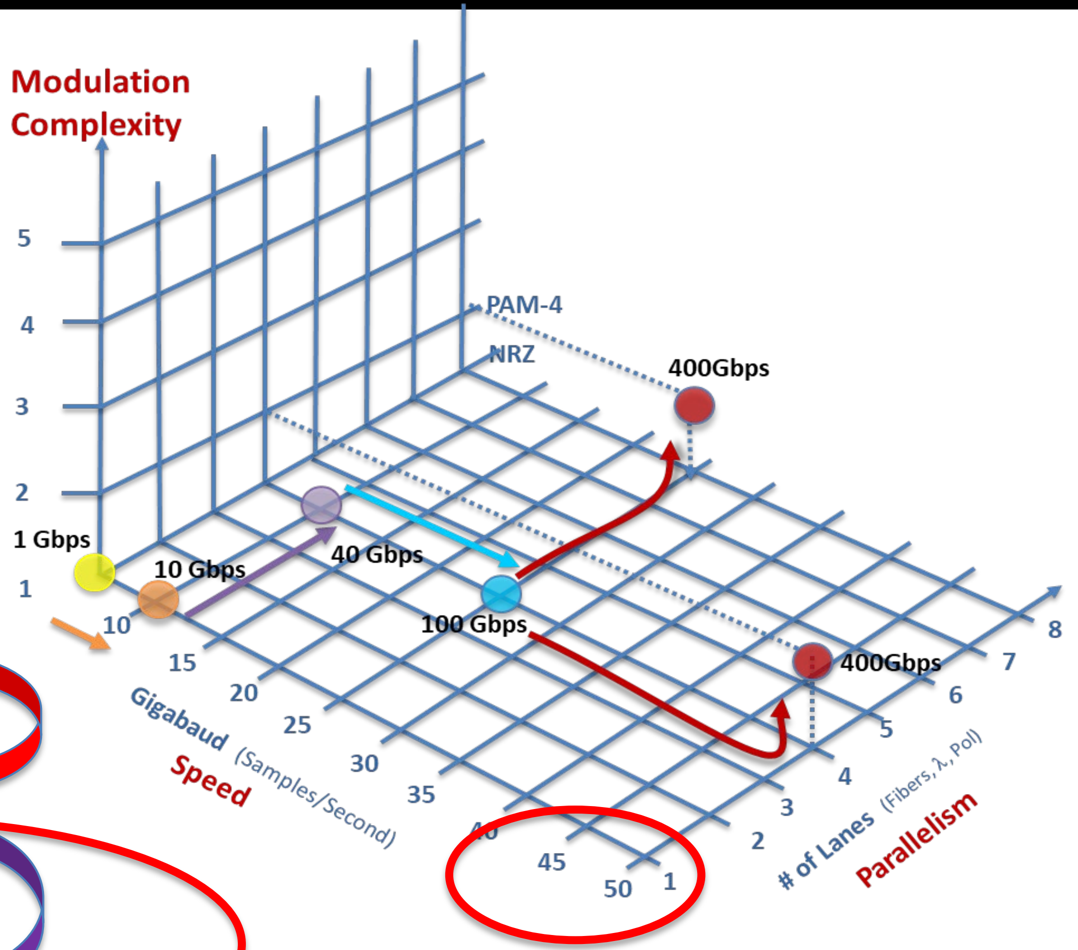
100Gbps: 4 lane x 25Gbps
(early 2010s)

Difficult

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

Much more difficult

800Gbps
1600Gbps




**Things get tougher with increasing data rates**

*Source: Lightwave Logic*

# Traffic capacity: road analogy

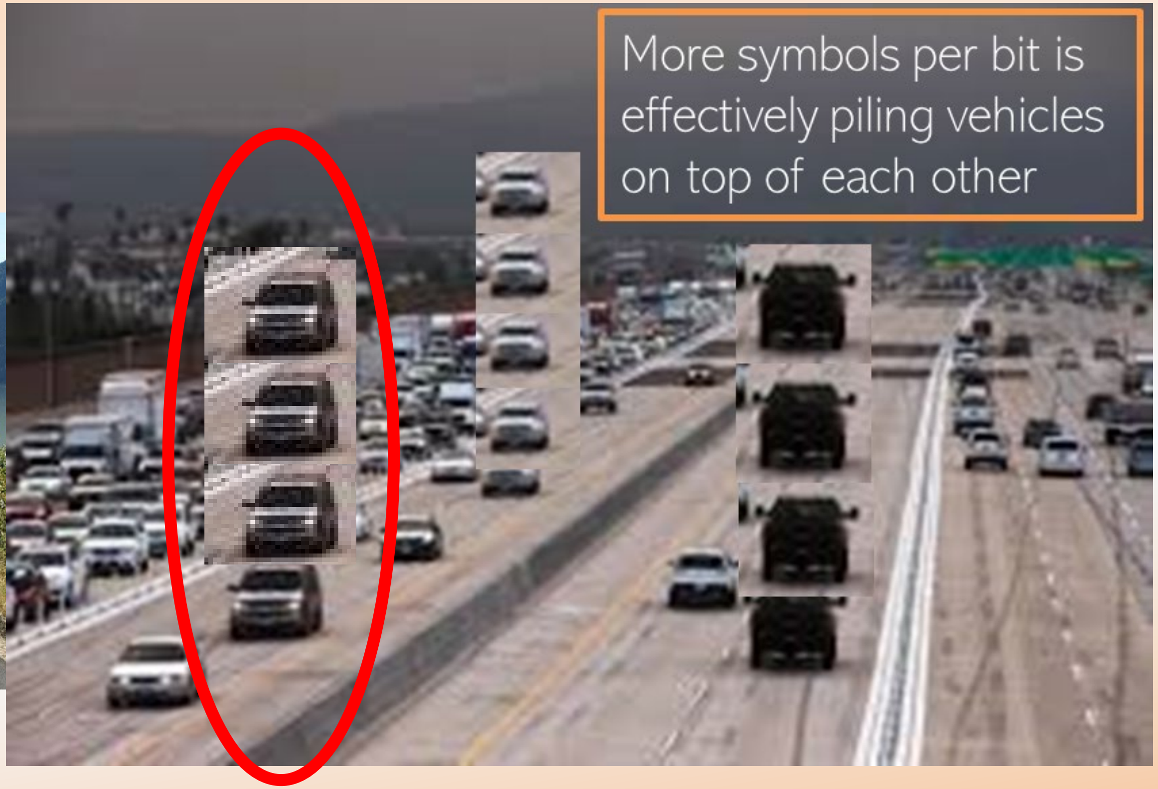
Good roads: Faster cars: more traffic capacity

More lanes: more traffic capacity

Already did the easy things like paving the road and adding more lanes

# Traffic handling: road analogy




Industry has already done the harder stuff like ‘higher order modulation’

# What about speed?

Still ~60 mph

10 mph → 60 mph

Speed has hit a plateau…

# Speed limited by conventional photonics

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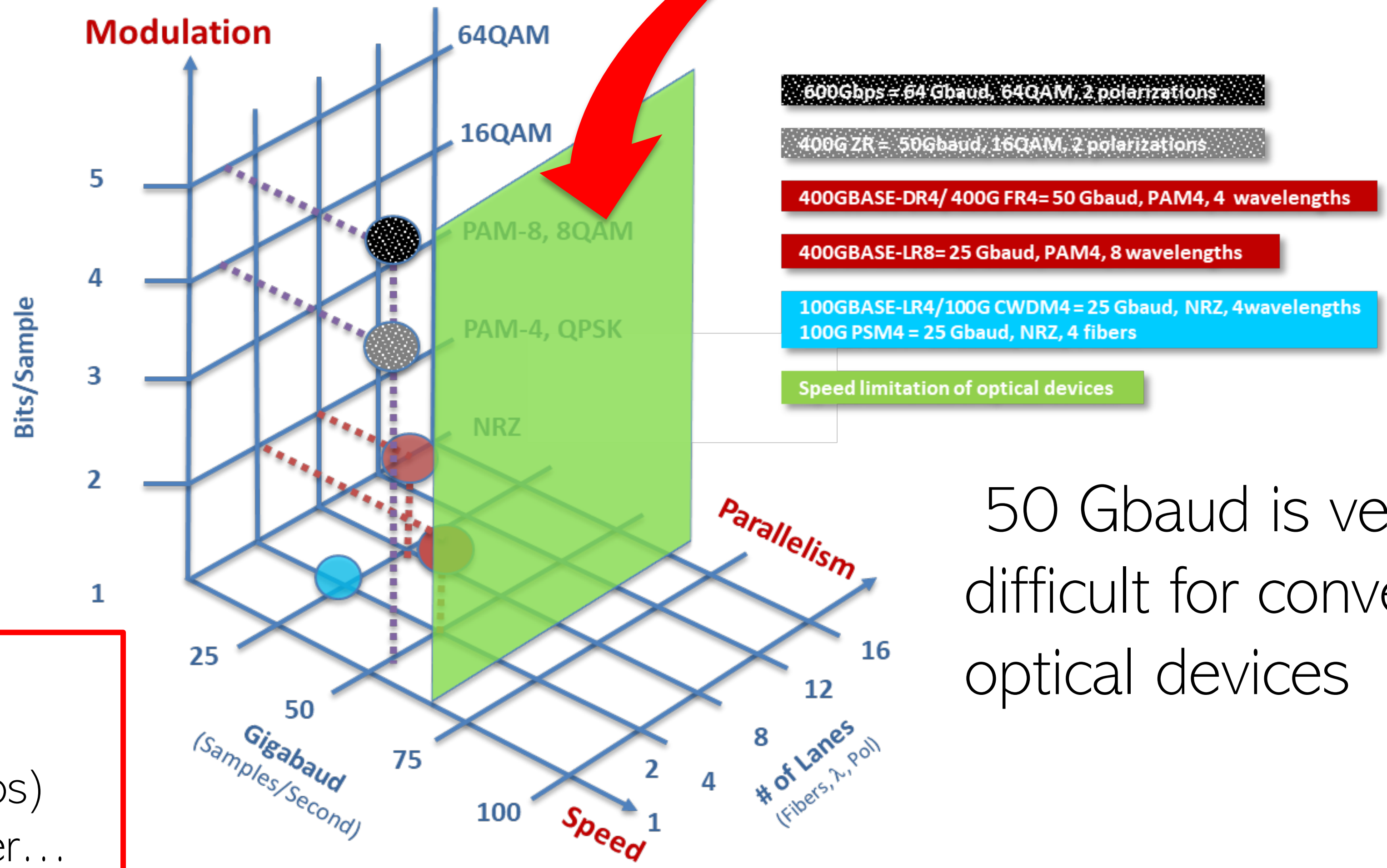



50 Gbaud is very difficult for conventional optical devices

In optical analog metrics of GHz, >35GHz (50Gbps) things get tougher…

**Speed limited by device physics**

# Plastic polymers break the speed limit…




Polymers are faster than other technologies

**Polymers double the native data traffic to 100Gbps (before counting multiple lanes, stacking…)**

 

# Innovation to break the speed barrier

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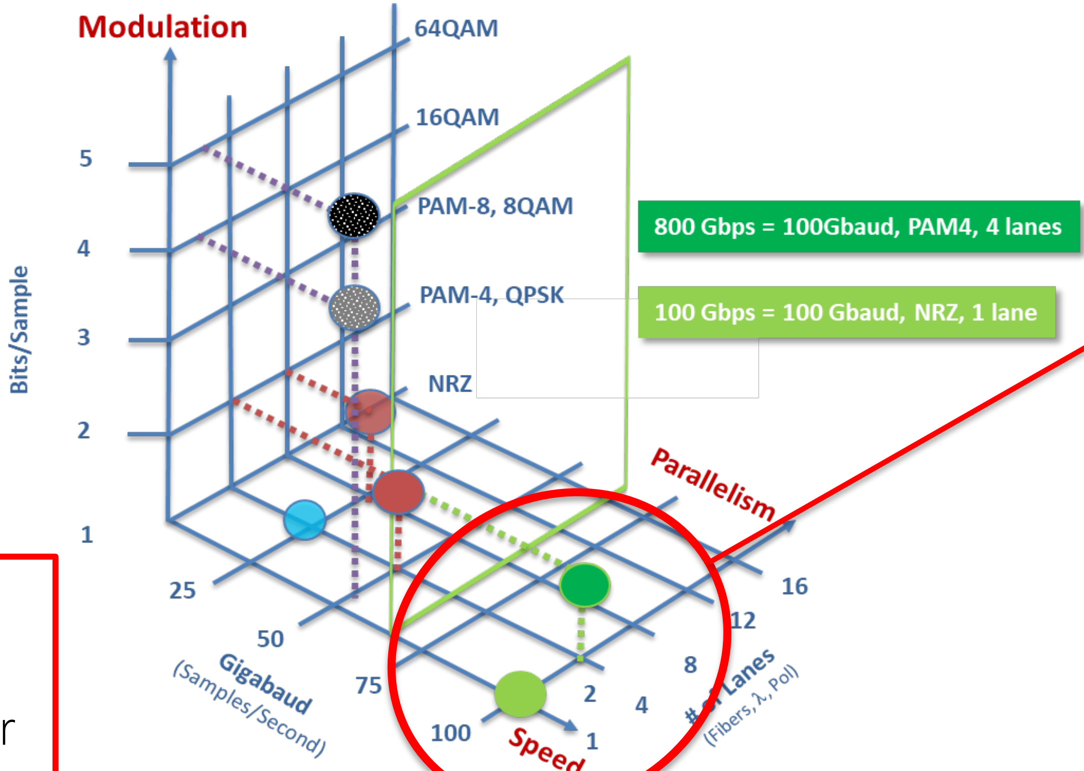
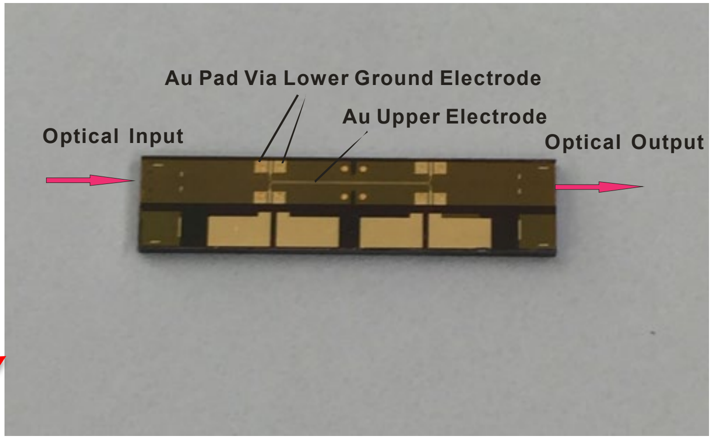



Source: Lightwave Logic (LWLG)




In optical analog metrics ~70GHz (100Gbps, NRZ or 200Gbaud, PAM4) is a challenge

- *Options can be:*
- 100G, 1V
  - 100Gbaud, NRZ, OOK
- 400G, 1V
  - 4 Channel x 100G NRZ, OOK
- 800G, 1V
  - 4 Channel x 100G, PAM-4

**Renewed ability to grow traffic capacity**

# Electro-Optic Response on Lightwave Component Analyzer

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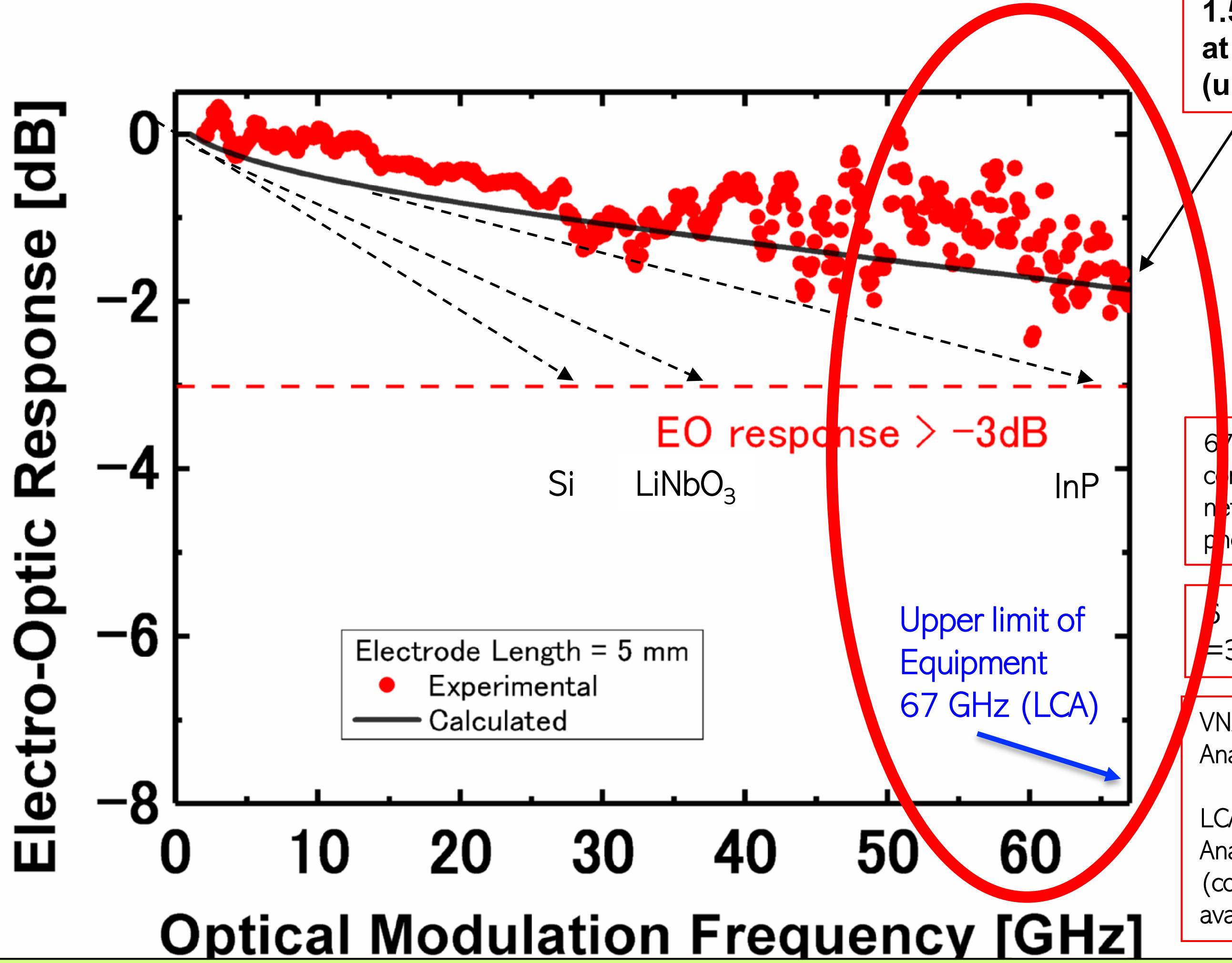


**1.5dB reduction at 67GHz (upper limit of LCA)**

Other optical modulators: $LiNbO_3$ = 40GHz, Si = 30GHz, InP = 60-70GHz

67GHz Lightwave component analyzer (vector network analyzer+ photodetector)

[illegible] dB reduction (VNA) =3 dB reduction (LCA)

VNA: Vector Network Analyzer 110GHz

LCA: Lightwave Component Analyzer 67GHz (commercially available)

In optical analog metrics ~70GHz is more than the equipment can handle…

**Extrapolated 3dB bandwidth of ~120GHz for EO response**

*Source: Lightwave Logic (LWLG); Yasufumi Enami (University of Kochi, Japan; University of Arizona)*

# EO frequency response measurements

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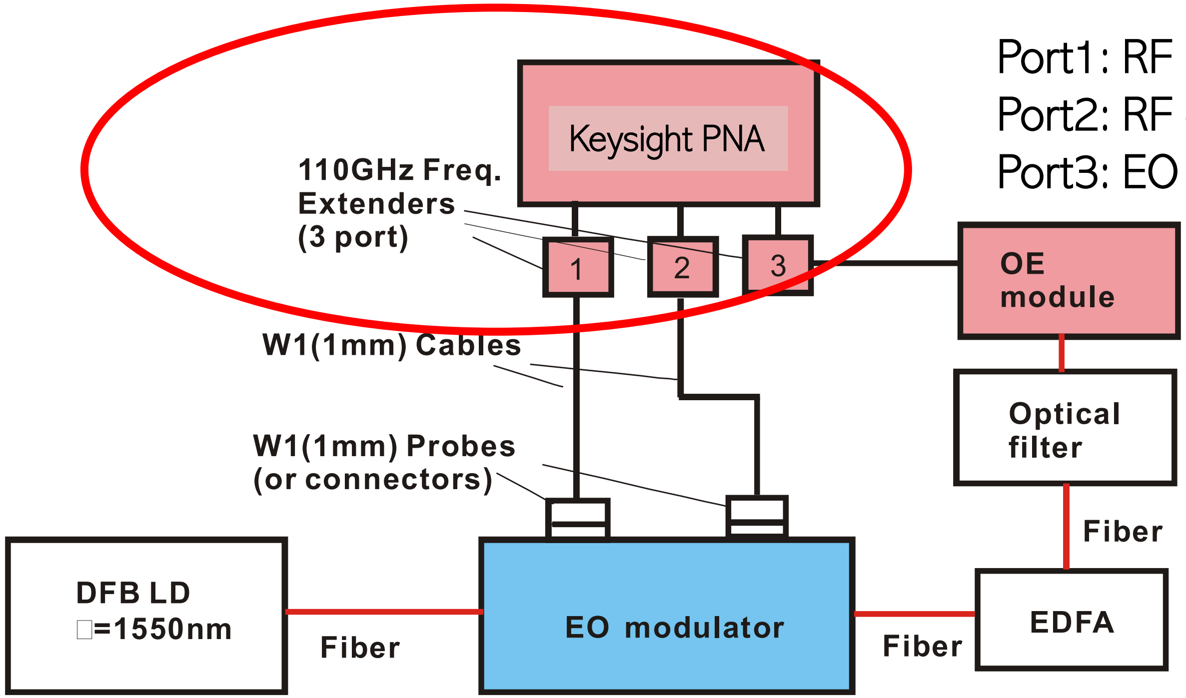


Port1: RF input
Port2: RF output
Port3: EO response

New equipment for 110GHz optical analog bandwidth: designs can be optimized

PNA: Vector network analyzer
EDFA: Er doped fiber amplifier
OE : Opto-electric
DFB LD: Distributed feedback laser diode

Port 1 and 2 for EE S21 and S11
Port 1 and 3 for EO S21

**State-of-the-art 110GHz measurement set-up**

 

# EO Polymer RWG Modulator

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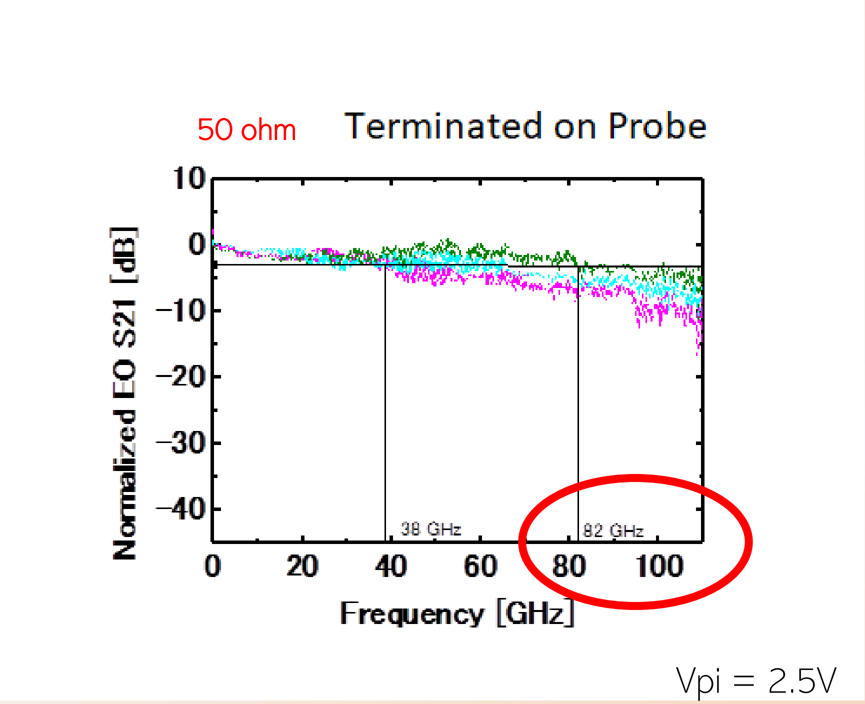
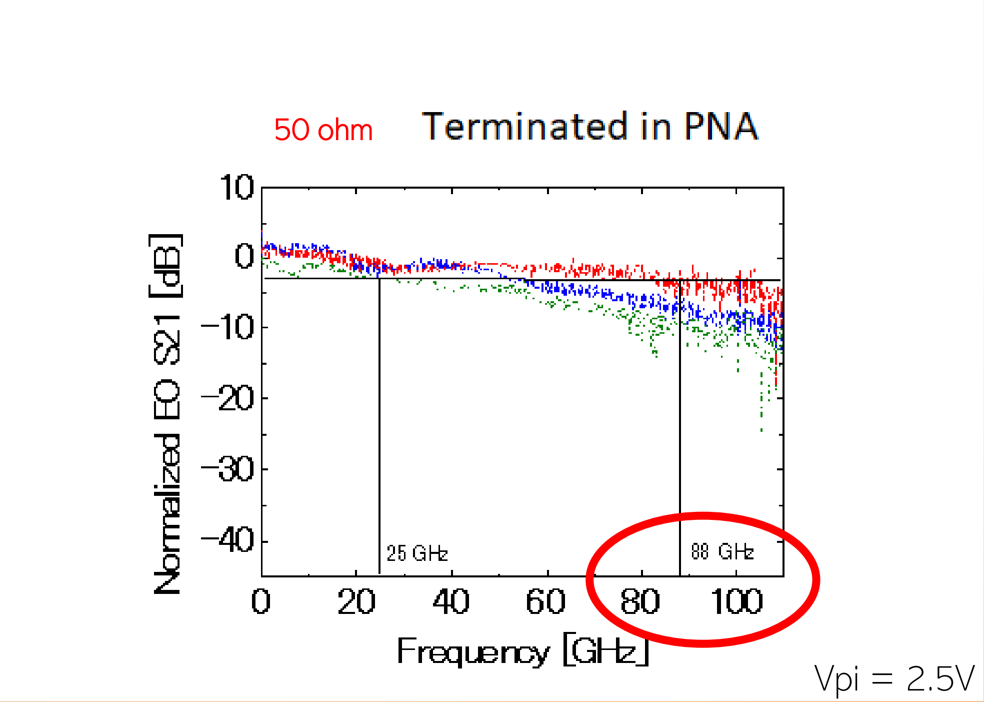
- Polymer modulator analogue optical bandwidth



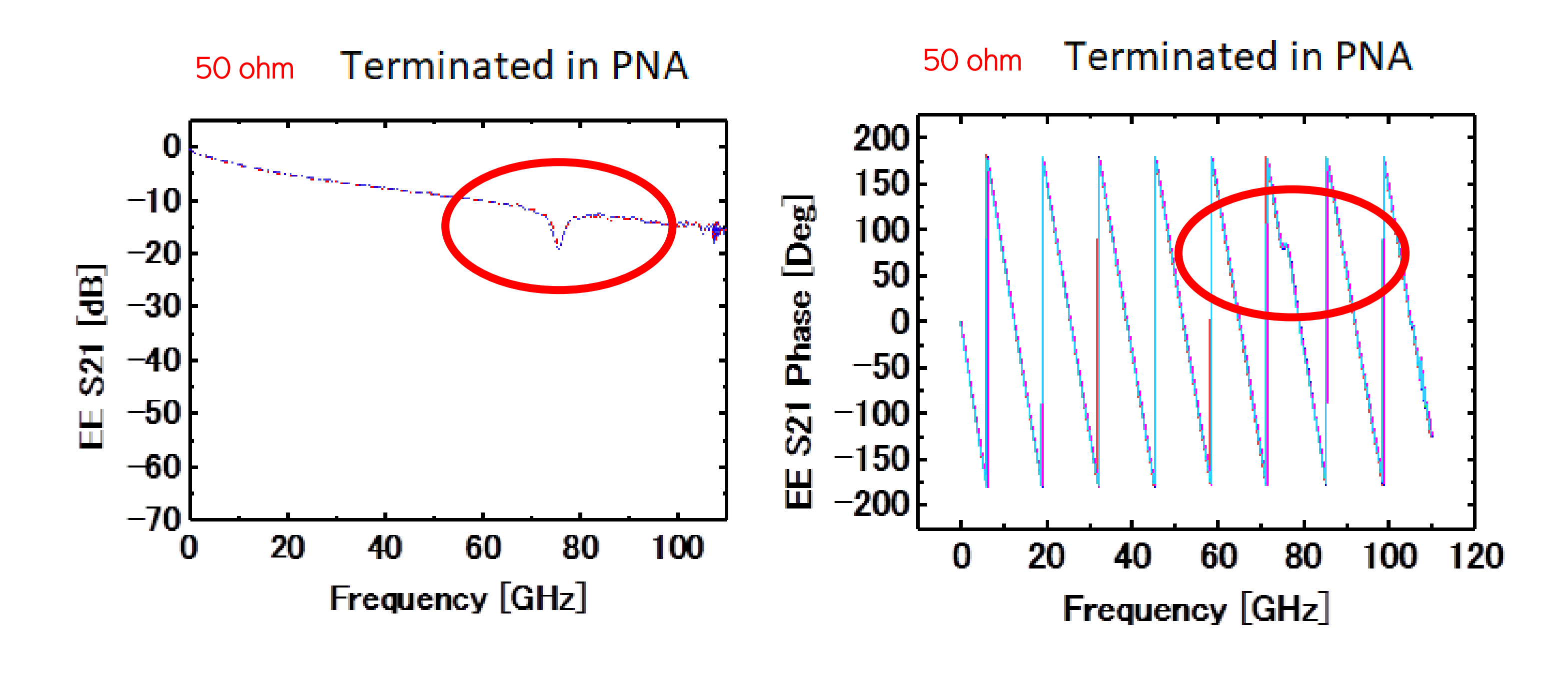

Measurement at >70GHz is very sensitive

# Electrical characterization

- EE S21 linear magnitude and phase
  - With small calibration glitch at ~75GHz

EE S21 magnitude response is very smooth and predictable



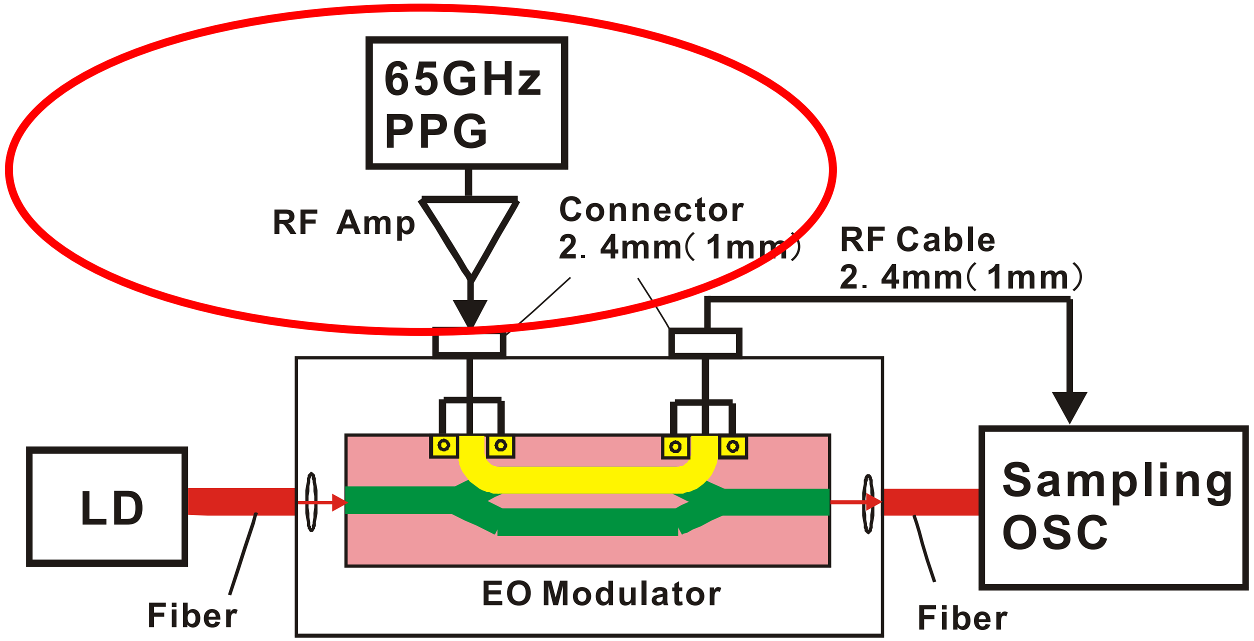

EE S21 phase response is very linear and predictable

Smooth EE S21 magnitude

# Eye diagram measurements






Packaged device

Packaged devices group A :1mm and 2.4mm connectors
Packaged devices group B : 2.4mm connectors

LD: Laser diode
PPG: Pulse generator (BERT)
OSC: oscilloscope

Packaged modulator set-up

# Eye diagram status

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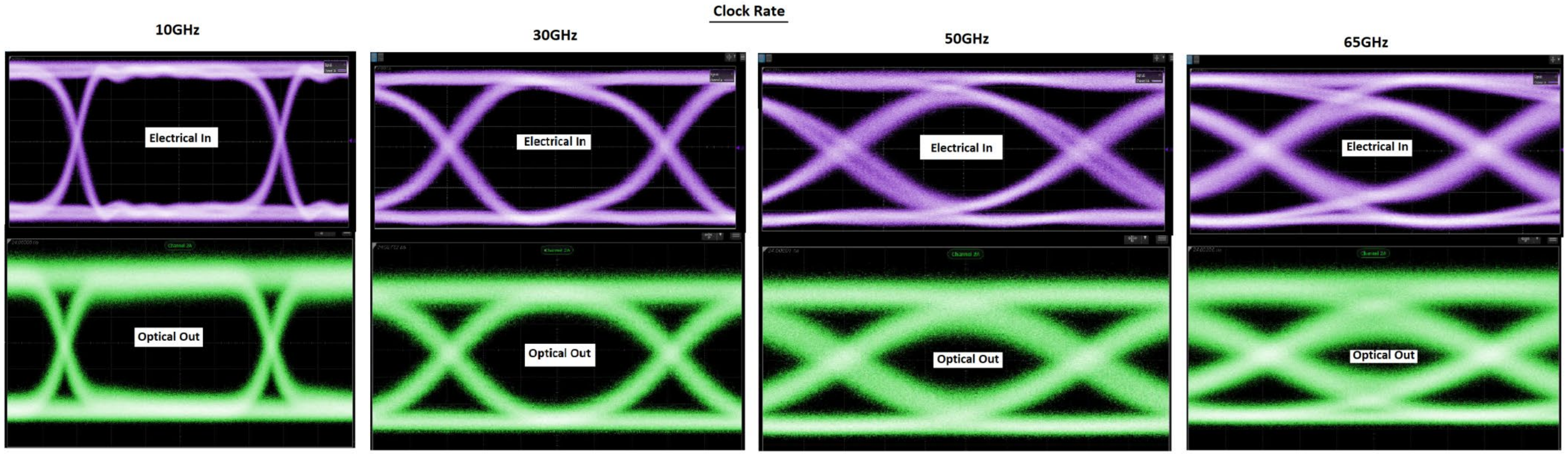
- Using DCA/BERT system
- Careful measurements of packaged polymer MZ
- Optical eyes follow input electrical signal well
- Open eyes at 65GHz (NRZ)




Eye diagram partly limited by input signal

# TDR measurement capability review

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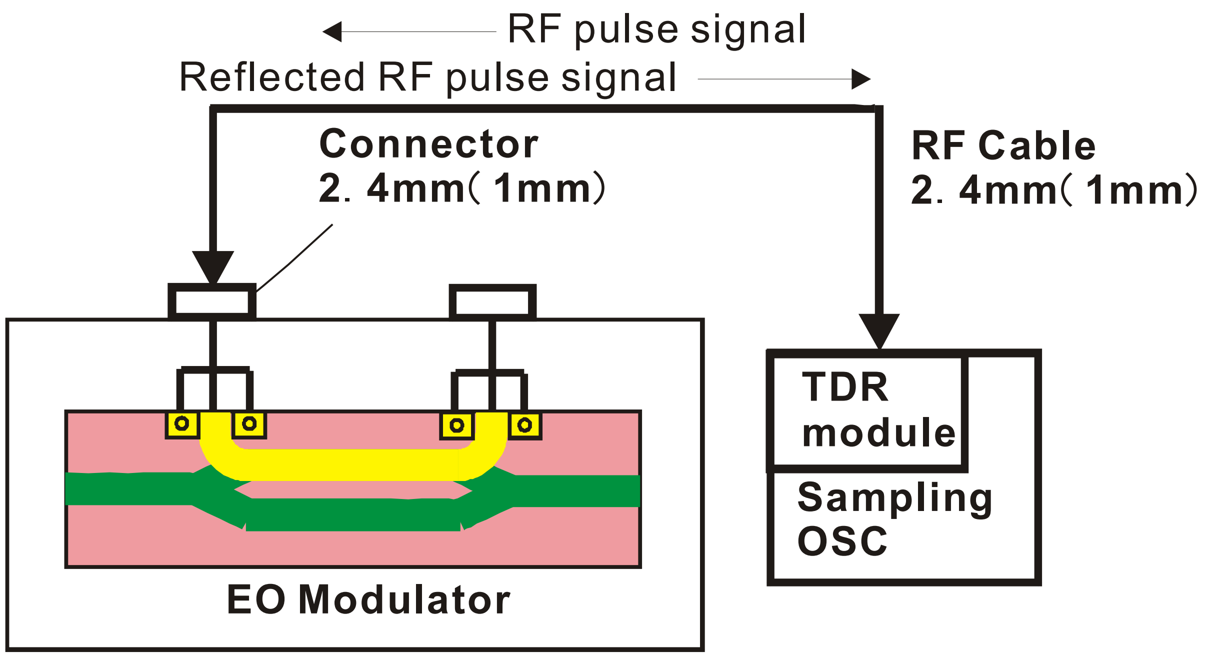


TDR: Time domain reflectometry
Examine impedance matching in packaged device

Packaged devices group A :1mm and 2.4mm connectors
Packaged devices group B : 2.4mm connectors

Checking measurement capability through reflected signaling

# TDR to check measurement capability

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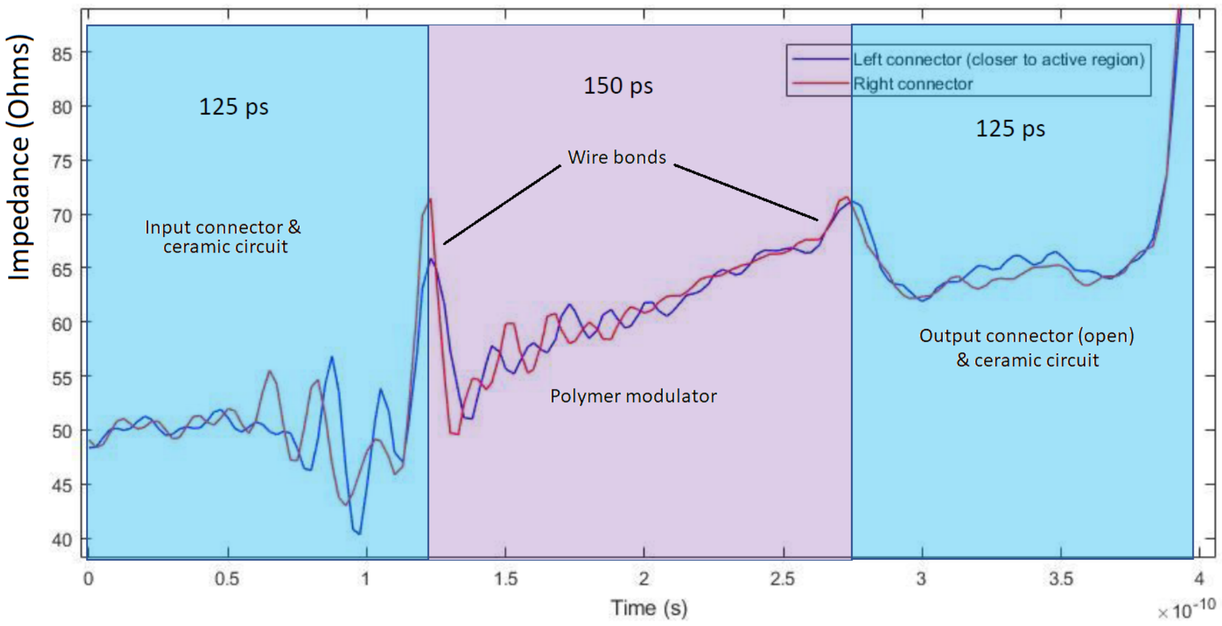
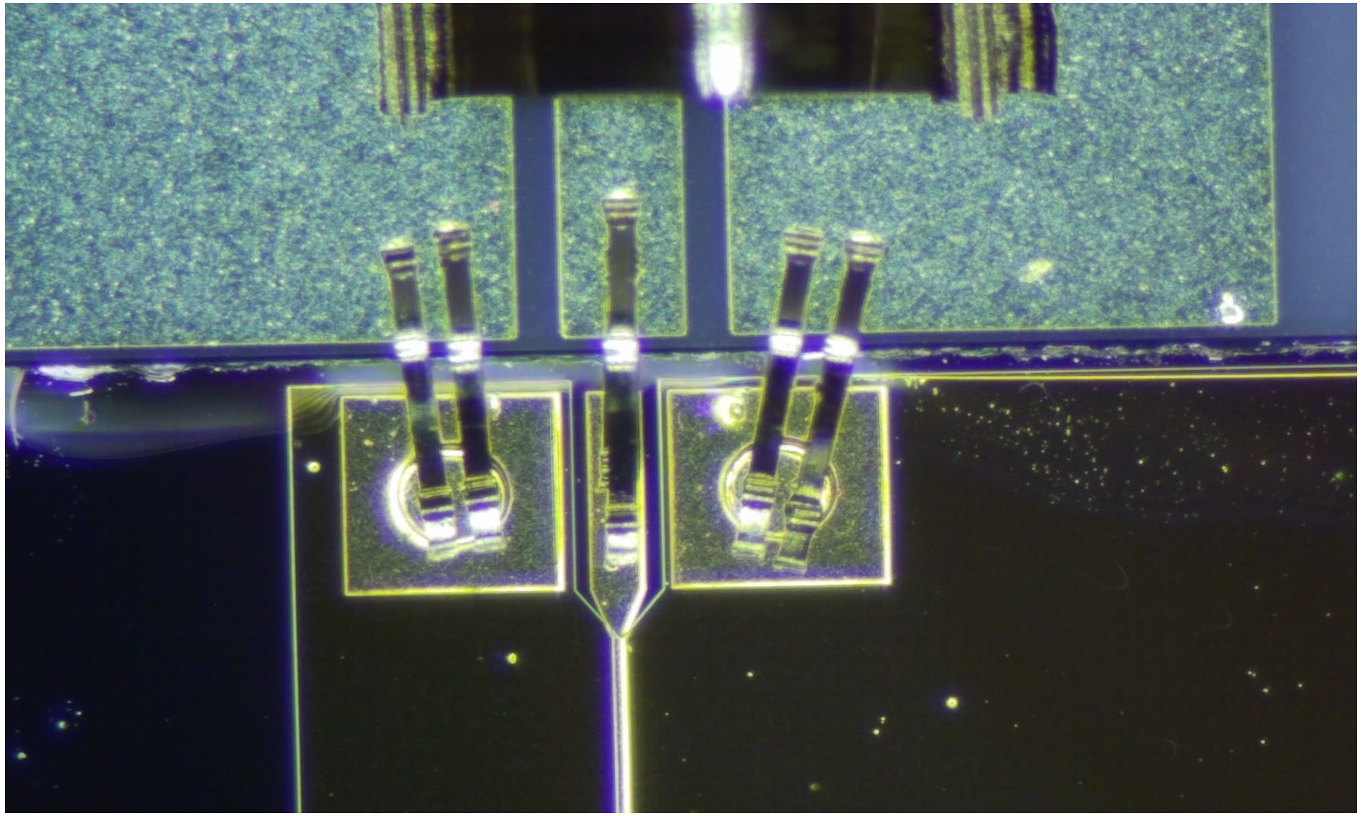
- Using TDR from Keysight
- TDR measurements allows the determination of impedance discontinuities along the rf path and assists in making improvements
- TDR measurements show reflections that need to be optimized




**TDR response to check measurement capability**

# Bond-ribbon Termination



TDR helps reduce reflections and allows improved designs

# Delivering radical innovation…

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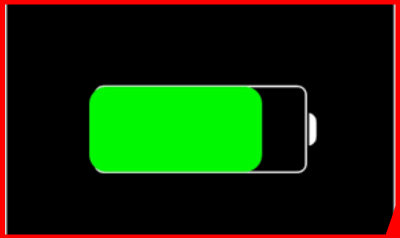
Photonics must deliver solutions:

**Faster devices**
(100GHz+)


**Lower Power**
(Low voltage)



**Lower cost**
(Easy fab)

**Robust**
(Stable)

To enable faster, lower power, lower cost internet…

*Source: Lightwave Logic (LWLG)*

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# Lower power



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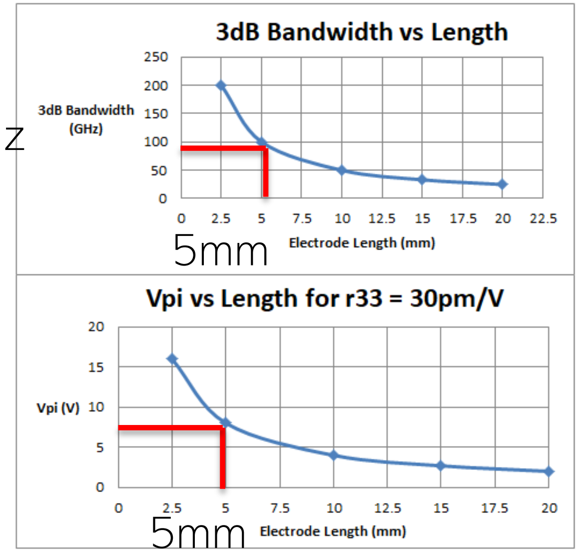
# Importance of Larger $r_{33}$

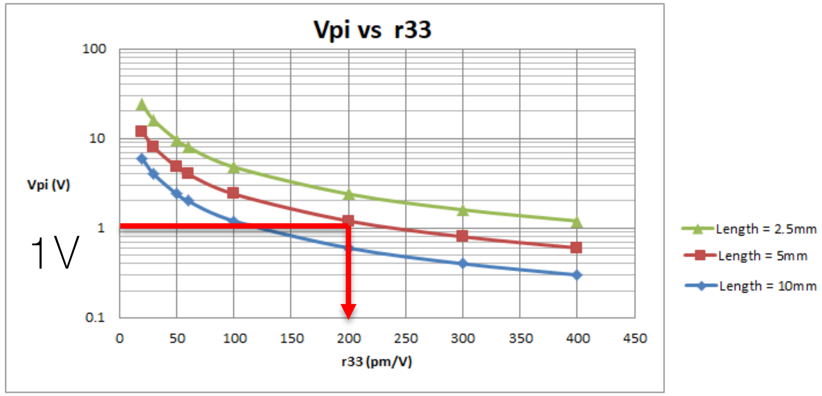


- Frequency response is inversely proportional to electrode length
  - Shorter electrode → More Gbps
- **BUT** Vpi is **ALSO** inversely proportional to electrode length
  - Shorter electrode → Larger Vpi
- Only free variable is $\mathbf{r_{33}}$
  - Larger $r_{33}$ → Shorter electrode → More Gbps → Same or Smaller Vpi

80+GHz

6-7V




~200pm/V

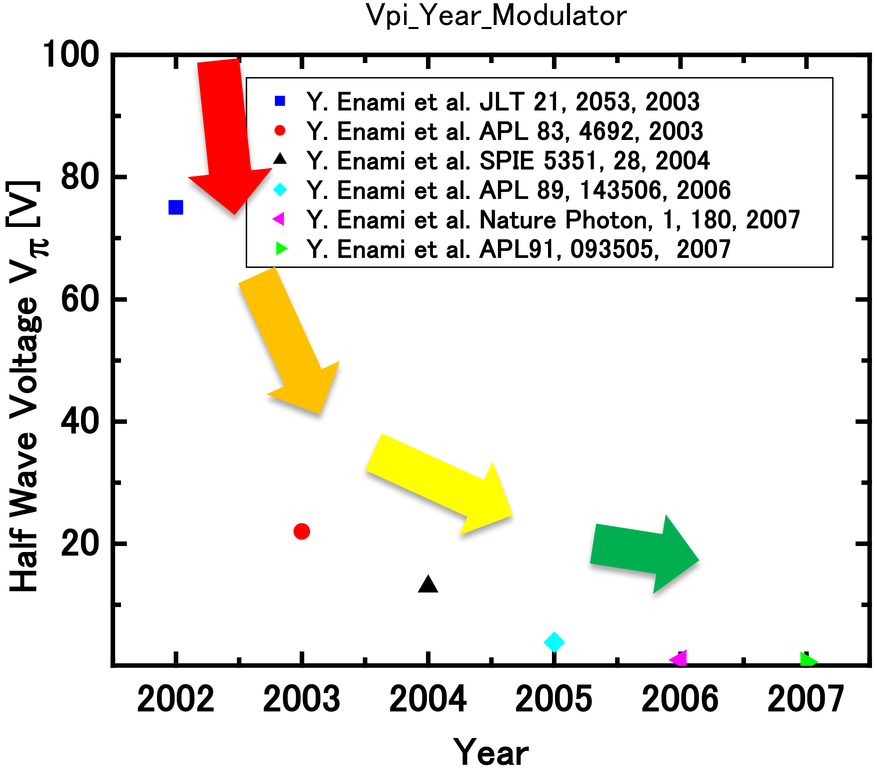
**Large $r_{33}$ is key to high performance and low voltage**

# Direct drive CMOS → saves power



- Lower voltage operation save power
- Also means the modulators can be driven directly from a CMOS chip
- No driver chips necessary
  - Saves even more power
  - Also saves $$$




*Source: Lightwave Logic (LWLG); Yasufumi Enami (University of Kochi, Japan; University of Arizona)*

Polymer modulators are *driverless, low power, and save $$$*

# Delivering radical innovation…

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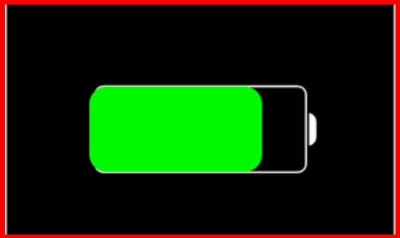
|   |  |  |  |

To enable faster, lower power, lower cost internet…

Source: Lightwave Logic (LWLG)

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# Lower cost…



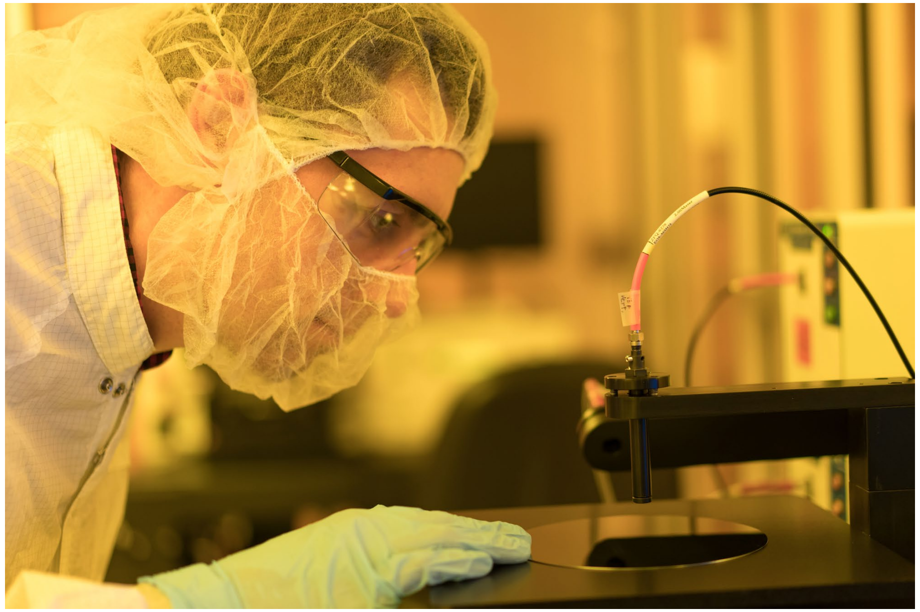
*Fastest by Design*

# Simple, low cost fabrication



Fabrication equipment and process is simple

- No exotic equipment needed
  - Standard photolithography to pattern
  - Wafer scalability
  - Minimize cycle time



**Lower costs can be enabled through simplicity in fabs**

# Our competitive advantage starts with our materials

- Our Perkinamine™ family of materials are proprietary and we control the synthesis in-house.
- We have additional advantages through control of the whole stack—from materials to device and package designs. This synergy gives us more knobs with which to optimize performance and cost.

**Our active molecules are of similar complexity to medical drugs**
**Their performance characteristics can be tailored for each application**

Lower costs can be enabled through chemistry design

# Integrate platforms → Hybrid solutions

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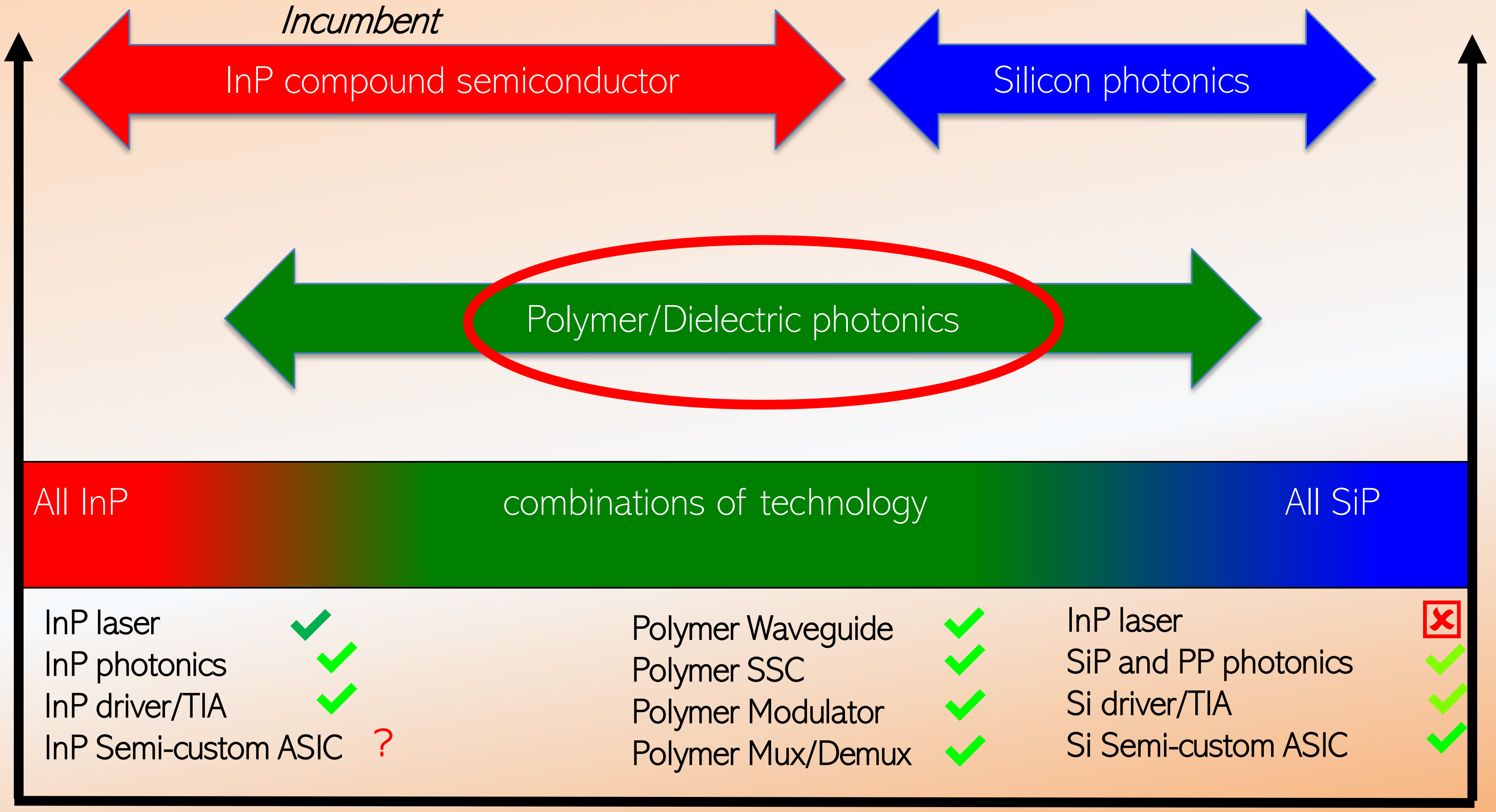


**Lower costs enabled through integration of hybrid technologies**

# Delivering radical innovation…

LIGHTWAVE LOGIC™

Photonics must deliver solutions:

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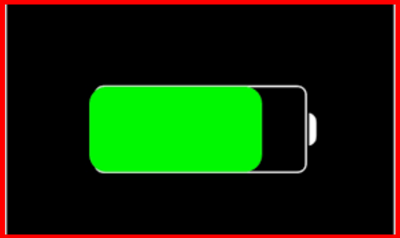
| --- | --- | --- | --- |
|  |  |  |  |



To enable faster, lower power, lower cost internet…

Source: *Lightwave Logic (LWLG)*

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# Robust…



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# PIC semiconductor robustness/reliability

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- Telecommunications always relied on Telcordia testing (GR-468 etc)
  - 10-20 year lifetime, low FIT rates, accelerated testing
- Datacommunications (datacenters) looked at simplifying R&QA to reduce cost
  - Recent datacenter requirements proposed 3yr fork-lift equipment changes, and reduced R&QA expectations
  - Today's datacenter folks are now looking to re-establish high reliability testing to reduce failure rates from 1000s of photonics equipment
- Net net → R&QA is still critical and needs to be taken very seriously
  - Next generation PICs must aim towards Telcordia requirements

R&QA needs to be aimed between datacom and telecom today

 

# Electro-optic polymers have a negative perception

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- Universal agreement on the EO performance of poled polymers
  - For example: 100GHz BW, Velocity match, Low Vpi, High r33…
- Universal *skepticism* on the stability of that performance.
  - "Organic isn't as stable as inorganic"
  - The same arguments were made against LCDs and OLEDs also…
- A key technical challenge facing EO polymers:
  - *Stabilizing the meta-stable state…*

Stability is one of the keys to build positive perception in polymers

 

# Stabilizing a meta-stable state

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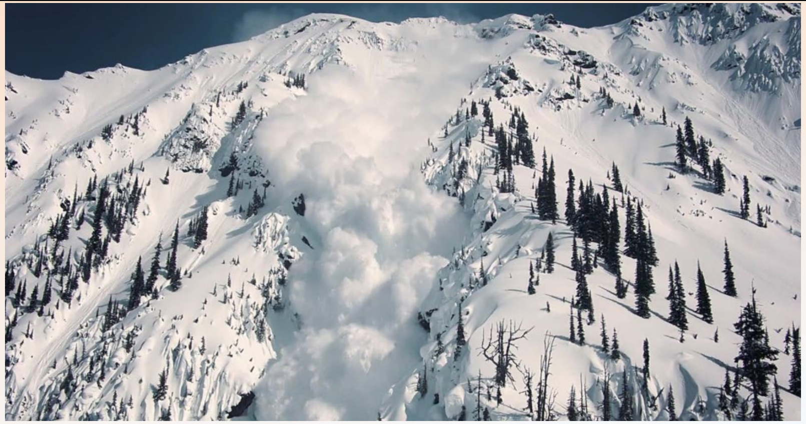
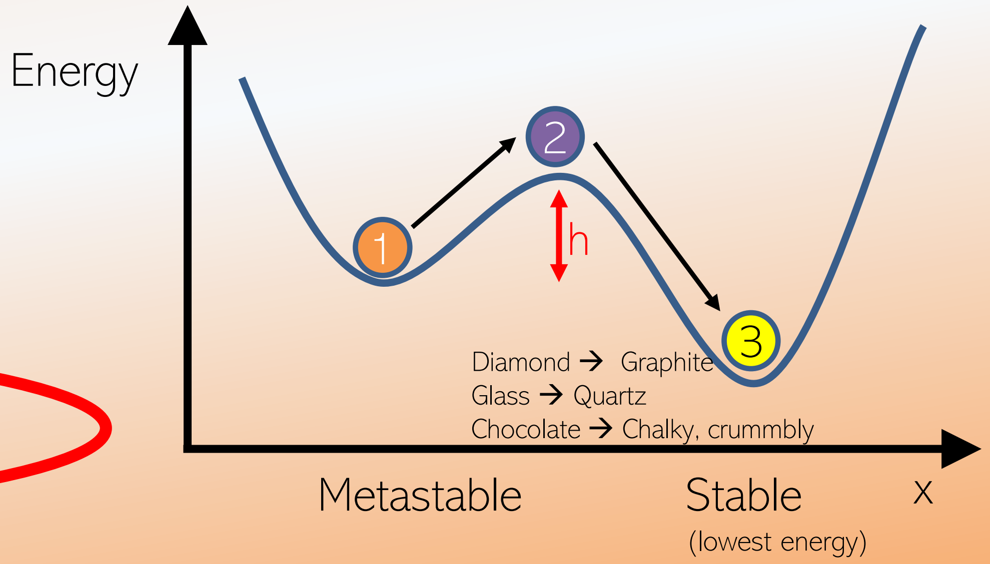
- The lowest energy state 3 is for all the snow to be at the bottom of the mountain. The system will relax (spectacularly) from 1 to 3 if sufficient energy (h) is applied.
- Yet we ski down mountains safely all the time because ski resorts can manage the barrier height of h:
  - Avalanche h can be set off by; skier triggering, sound, mortar, ski patrol



- Many materials we encounter every day are metastable (e.g., diamonds, glass, chocolate)
- Metastability is not something to avoid, but rather control…
- We've engineered polymers to be more stable in a meta-stable state




**Engineering polymers for stability in a meta-stable state**

# Engineering the barrier height for stability

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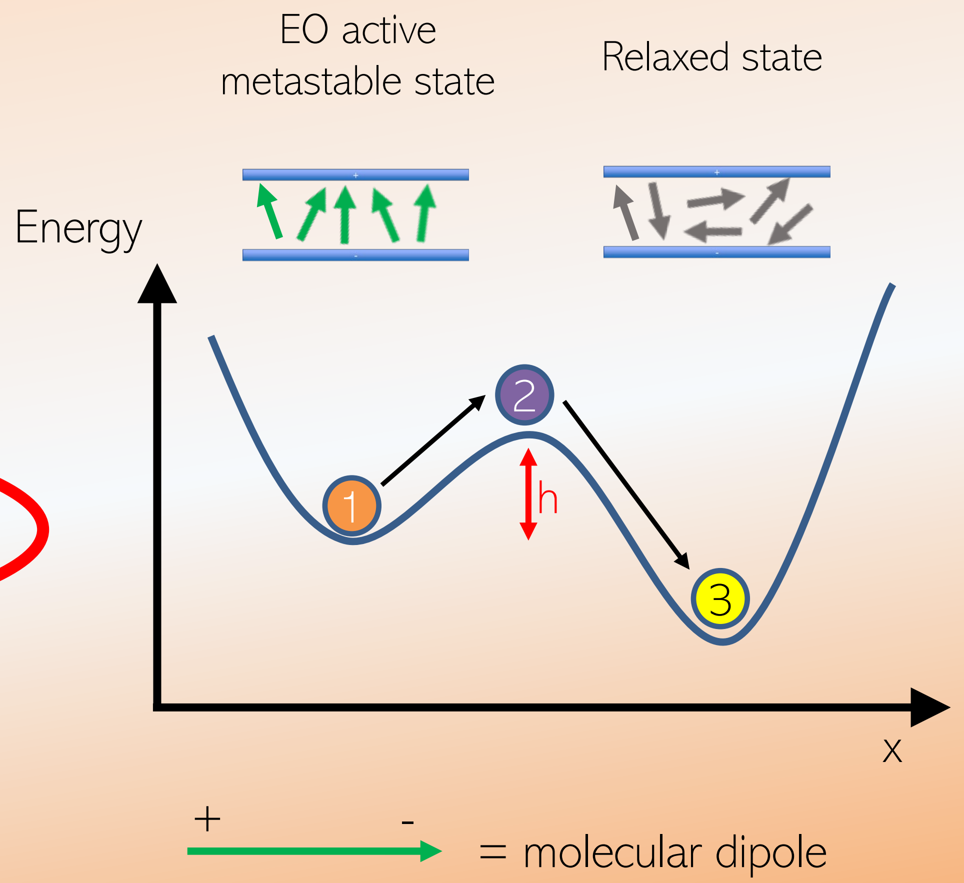
- Poled polymers will slowly relax to 3 at a rate controlled by barrier height h
- Engineering challenge is to make barrier h large
- No laws of physics need to be broken…

- h can be controlled by careful molecular design and the power of synthetic organic chemistry




**Barrier h can be engineered by molecular design**

# Optimizing the molecular design for stability

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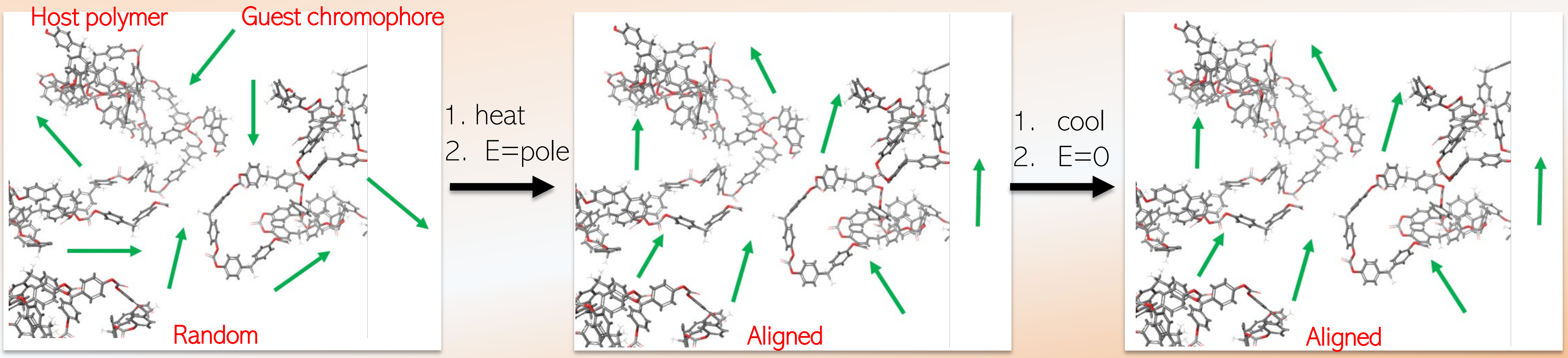
- The higher the rigidity of the polymer composite, the higher barrier h is (more stable)
- The more surrounded the chromophore dipoles are, the higher barrier h is (more stable)




- EO polymers are prepared by adding high concentrations of a “guest” chromophore to an amorphous “host” polymer.
- The composite is heated to the glass transition temperature to liquify the polymer and the poling field is applied to align the chromophores within the polymer matrix.
- The sample is cooled with the field applied to trap the poled order in the glassy state.

**Barrier h is optimized by mix of chromophore and polymer**

# Design strategy for increasing barrier h at the molecular level

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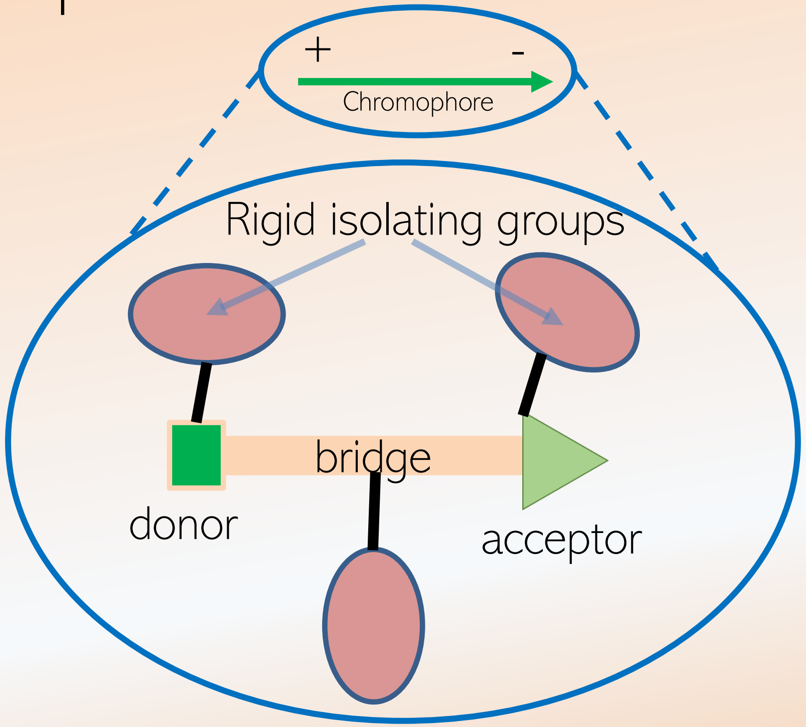
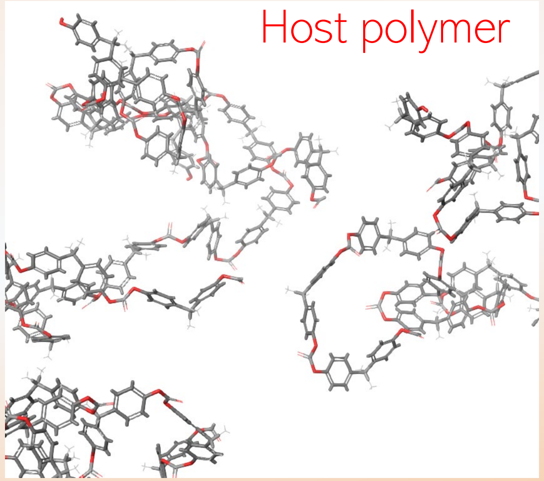
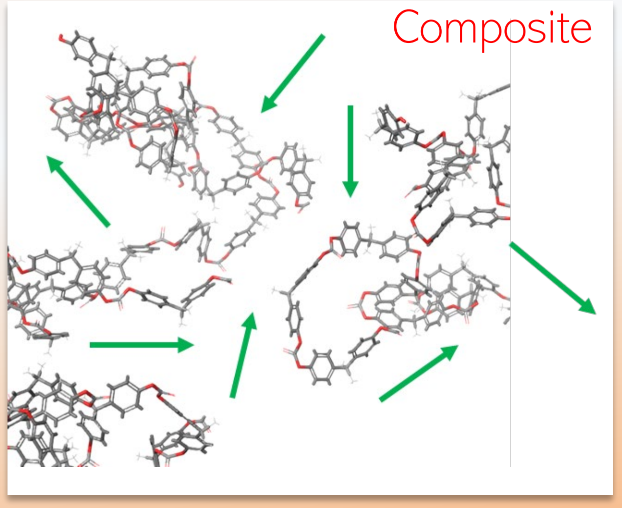
- Chromophores can be modified via synthetic organic chemistry to act as anti-plasticizers and increase the rigidity (*and barrier h*) of the composite polymer.




- Rigid isolating groups reduce dipolar interactions and *increase rigidity of polymer composite (h)*
- Rigid, high glass transition temperature ($T_g$) *increases h*
- Rigid, high glass transition temperature ($T_g$) *increases h*

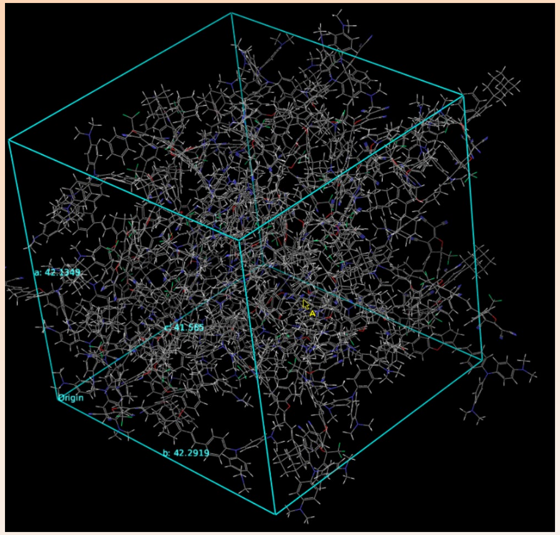
**Molecular design is critical**

Plasticizers typically softens or reduces h

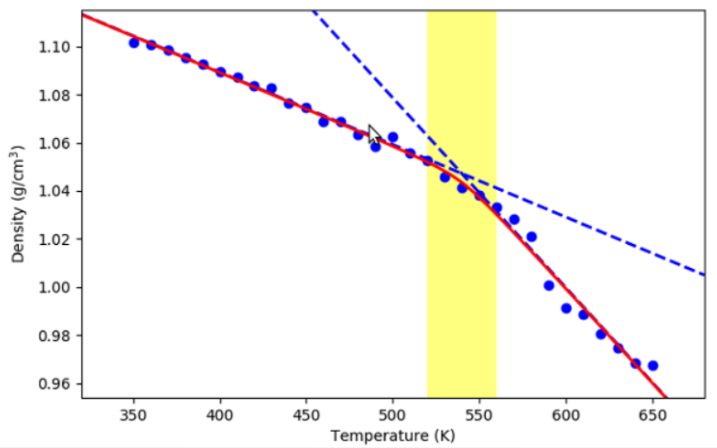
 

# Molecular Design: simulation guided design

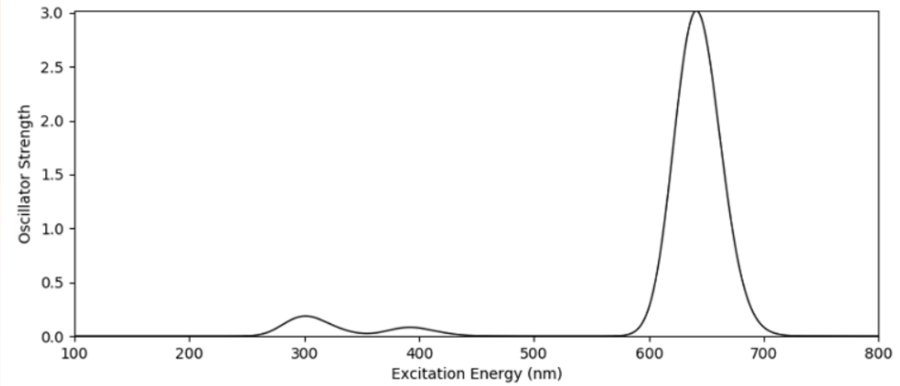





Glass transition temperature




Absorption




- Many interdependent parameters (besides rigidity of the composite) that need consideration: Dipole, Hyperpolarizability, Loss (absorption), Thermal stability, Poling efficiency, Solubility
- All of these are calculable with a combination of quantum mechanical (DFT) and molecular dynamics methods.
- Apply the same tools the pharmaceutical industry uses to engineer drugs and the display industry uses to engineer OLEDs to electro-optic polymers.

**Molecular design through simulation tools increases cycles of learning**

# Higher stability of meta-stable state

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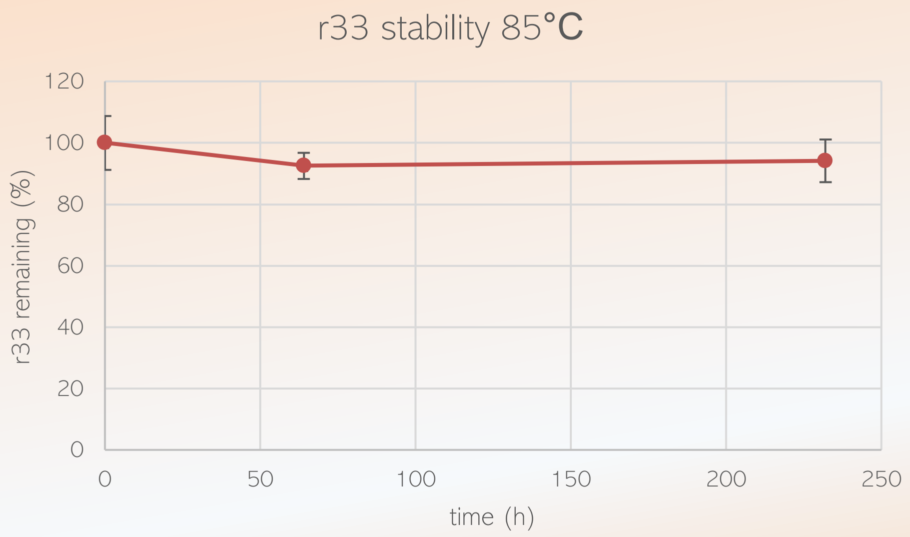
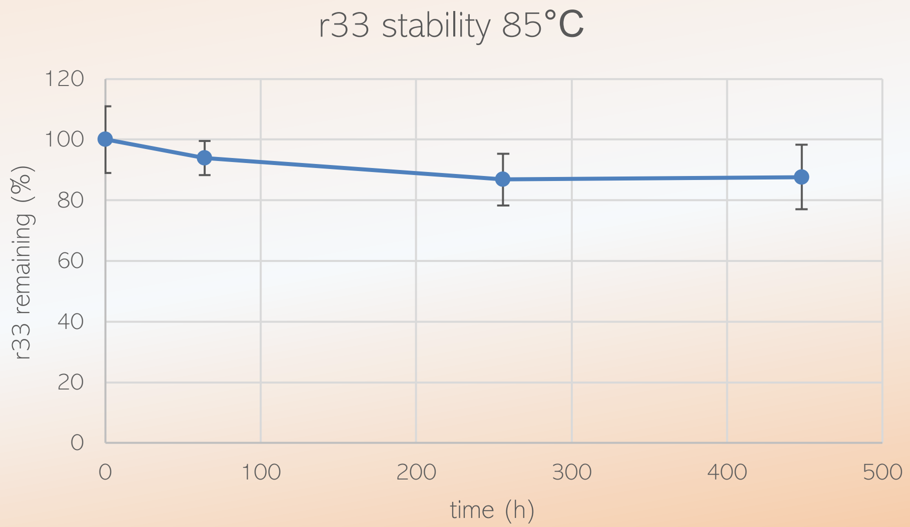
- Improved temporal stability of r33 @ 85°C



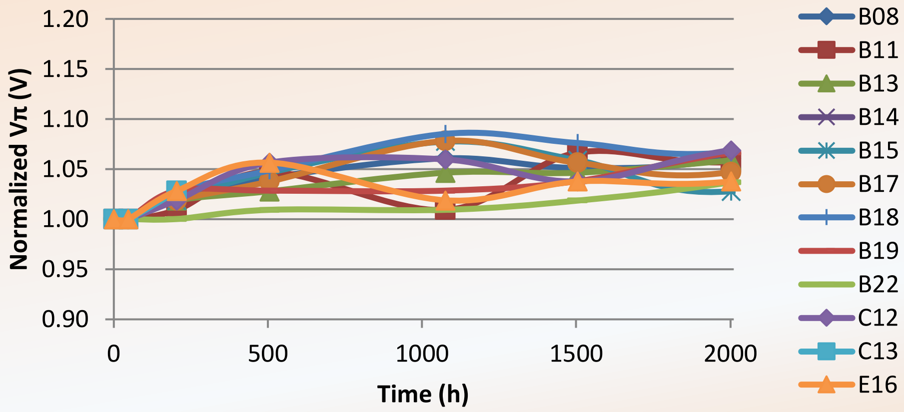

**Result of increasing the barrier h of meta-stable state**

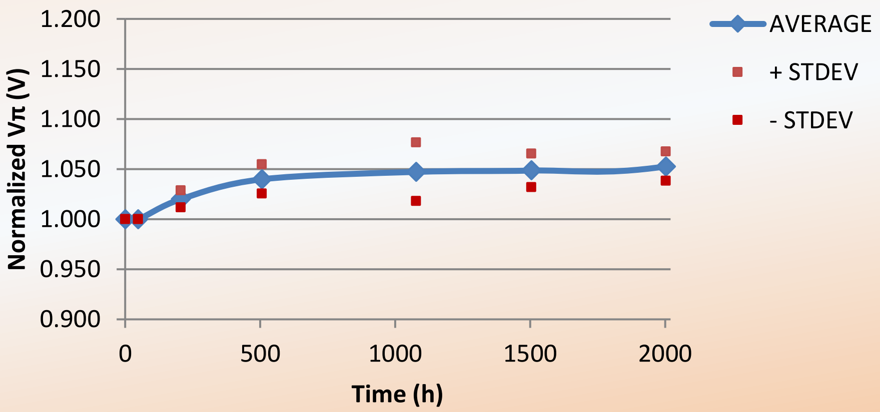
 

# Higher stability of meta-stable state



- Improved temporal stability of Vpi @ 85°C




Result of increasing the barrier h of meta-stable state

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OTCQB: LWLG

# Roadmap update



*Fastest by Design*

# Slide presentation will be posted at website

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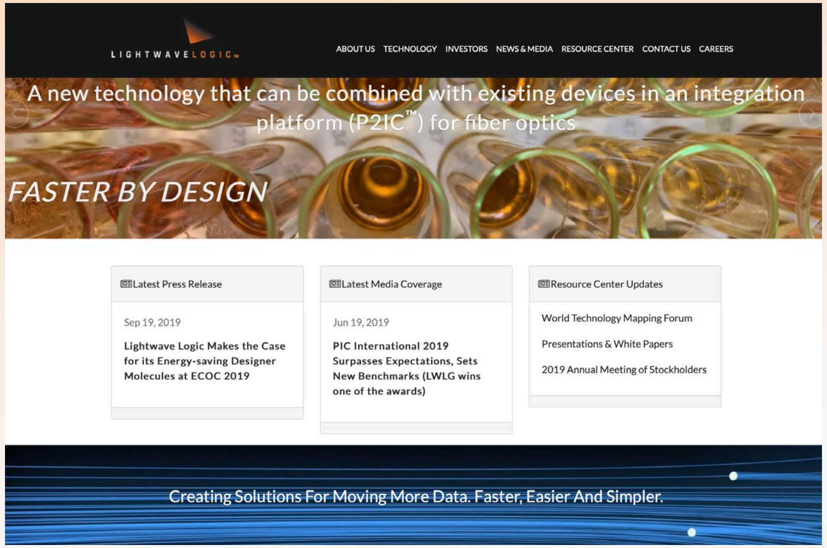


www.lightwavelogic.com

Sit back…relax…roadmaps *are very detailed…*

# Roadmaps: What did we predict in 2016?

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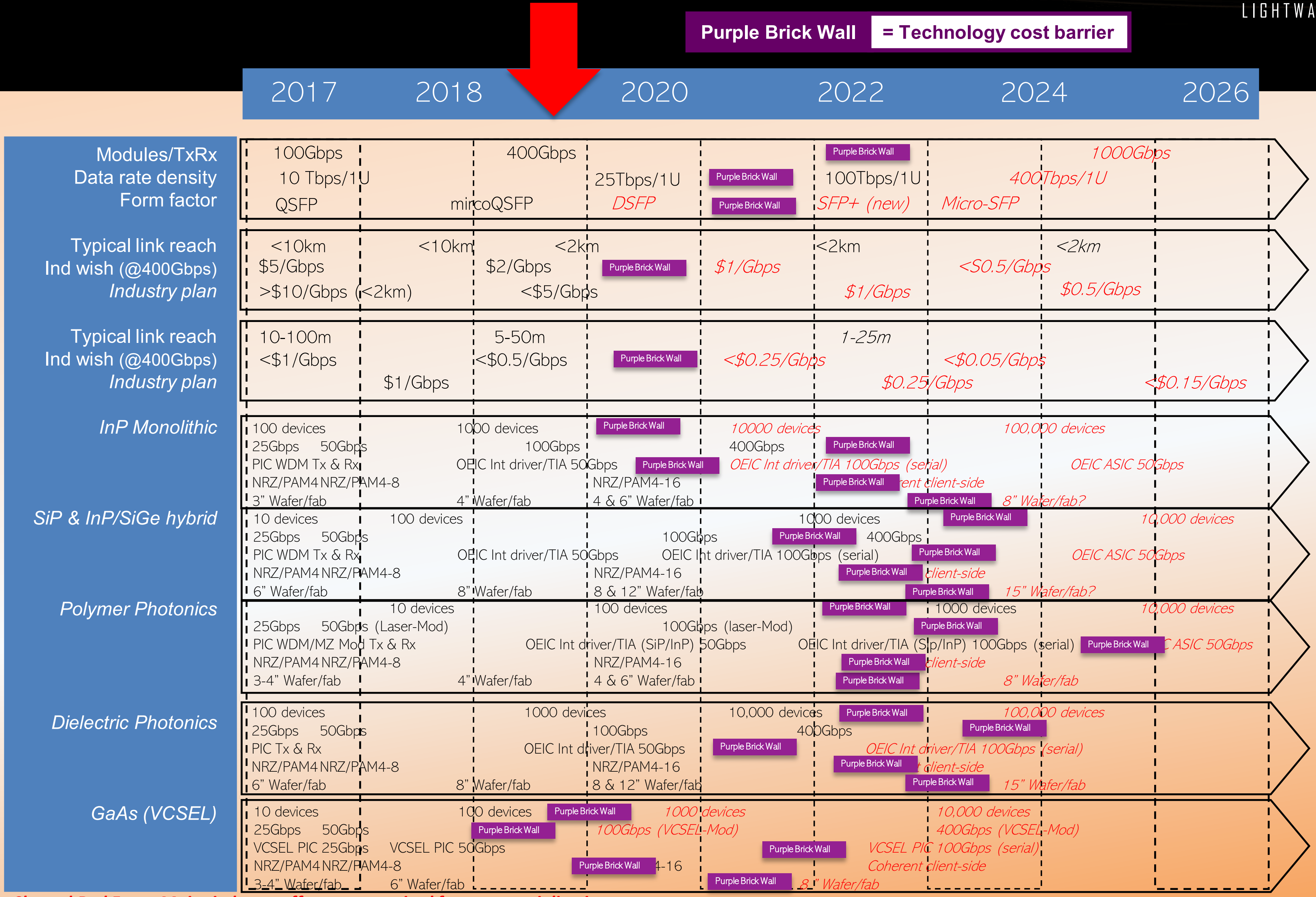
**Purple Brick Wall** **= Technology cost barrier**




***Slanted Red Font: Major industry efforts are required for commercialization***

**Source: Lightwave Logic**

# Actually pretty good → TxRx 400Gbps, <$5/Gbps, 50Gbps+ devices

**Purple Brick Wall** = Technology cost barrier

| | 2017 | 2018 | 2020 | 2022 | 2024 | 2026 |
|---|---|---|---|---|---|---|

**Modules/TxRx / Data rate density / Form factor**
- 100Gbps; 10 Tbps/1U; QSFP
- 400Gbps; 25Tbps/1U; microQSFP; *DSFP*
- Purple Brick Wall; Purple Brick Wall; Purple Brick Wall
- 100Tbps/1U; *SFP+ (new)*
- *1000Gbps*; *400Tbps/1U*; *Micro-SFP*

**Typical link reach / Ind wish (@400Gbps) / Industry plan**
- <10km; $5/Gbps; >$10/Gbps (<2km)
- <10km; <2km; $2/Gbps; <$5/Gbps; Purple Brick Wall
- *$1/Gbps*
- <2km; *$1/Gbps*
- *<2km*; *<$0.5/Gbps*; *$0.5/Gbps*

**Typical link reach / Ind wish (@400Gbps) / Industry plan**
- 10-100m; <$1/Gbps; $1/Gbps
- 5-50m; <$0.5/Gbps; Purple Brick Wall
- *<$0.25/Gbps*; *1-25m*; *$0.25/Gbps*
- *<$0.05/Gbps*; *<$0.15/Gbps*

***InP Monolithic***
- 100 devices; 25Gbps 50Gbps; PIC WDM Tx & Rx; NRZ/PAM4 NRZ/PAM4-8; 3" Wafer/fab
- 1000 devices; 400Gbps; OEIC Int driver/TIA 50Gbps; 4" Wafer/fab
- Purple Brick Wall; Purple Brick Wall; NRZ/PAM4-16; 4 & 6" Wafer/fab
- *10000 devices*; 400Gbps; *OEIC Int driver/TIA 100Gbps (serial)*; Purple Brick Wall; Purple Brick Wall; *Coherent client-side*; Purple Brick Wall
- *100,000 devices*; *OEIC ASIC 50Gbps*; *8" Wafer/fab?*

***SiP & InP/SiGe hybrid***
- 10 devices; 25Gbps 50Gbps; PIC WDM Tx & Rx; NRZ/PAM4 NRZ/PAM4-8; 6" Wafer/fab
- 100 devices; OEIC Int driver/TIA 50Gbps; 8" Wafer/fab
- 100Gbps; OEIC Int driver/TIA 100Gbps (serial); NRZ/PAM4-16; 8 & 12" Wafer/fab
- 1000 devices; Purple Brick Wall; 400Gbps; Purple Brick Wall; Purple Brick Wall; *client-side*; Purple Brick Wall; Purple Brick Wall
- *10,000 devices*; *OEIC ASIC 50Gbps*; *15" Wafer/fab?*

***Polymer Photonics***
- 25Gbps 50Gbps (Laser-Mod); PIC WDM/MZ Mod Tx & Rx; NRZ/PAM4 NRZ/PAM4-8; 3-4" Wafer/fab
- 10 devices; 4" Wafer/fab
- 100 devices; 100Gbps (laser-Mod); OEIC Int driver/TIA (SiP/InP) 50Gbps; NRZ/PAM4-16; 4 & 6" Wafer/fab
- Purple Brick Wall; 1000 devices; Purple Brick Wall; OEIC Int driver/TIA (SiP/InP) 100Gbps (serial); Purple Brick Wall; *client-side*; Purple Brick Wall
- *10,000 devices*; Purple Brick Wall; *OEIC ASIC 50Gbps*; *8" Wafer/fab*

***Dielectric Photonics***
- 100 devices; 25Gbps 50Gbps; PIC Tx & Rx; NRZ/PAM4 NRZ/PAM4-8; 6" Wafer/fab
- 1000 devices; 100Gbps; OEIC Int driver/TIA 50Gbps; NRZ/PAM4-16; 8" Wafer/fab; 8 & 12" Wafer/fab
- 10,000 devices; 400Gbps; Purple Brick Wall; Purple Brick Wall; Purple Brick Wall
- *100,000 devices*; Purple Brick Wall; *OEIC Int driver/TIA 100Gbps (serial)*; *client-side*; Purple Brick Wall; *15" Wafer/fab*

***GaAs (VCSEL)***
- 10 devices; 25Gbps 50Gbps; VCSEL PIC 25Gbps; NRZ/PAM4 NRZ/PAM4-8; 3-4" Wafer/fab
- VCSEL PIC 50Gbps; 6" Wafer/fab
- 100 devices; Purple Brick Wall; Purple Brick Wall; Purple Brick Wall; 4-16
- *1000 devices*; *100Gbps (VCSEL-Mod)*; Purple Brick Wall; Purple Brick Wall; *8" Wafer/fab*
- *VCSEL PIC 100Gbps (serial)*; *Coherent client-side*
- *10,000 devices*; *400Gbps (VCSEL-Mod)*

***Slanted Red Font: Major industry efforts are required for commercialization***

**Source: Lightwave Logic**

# New draft in 2019 → Where are we going?

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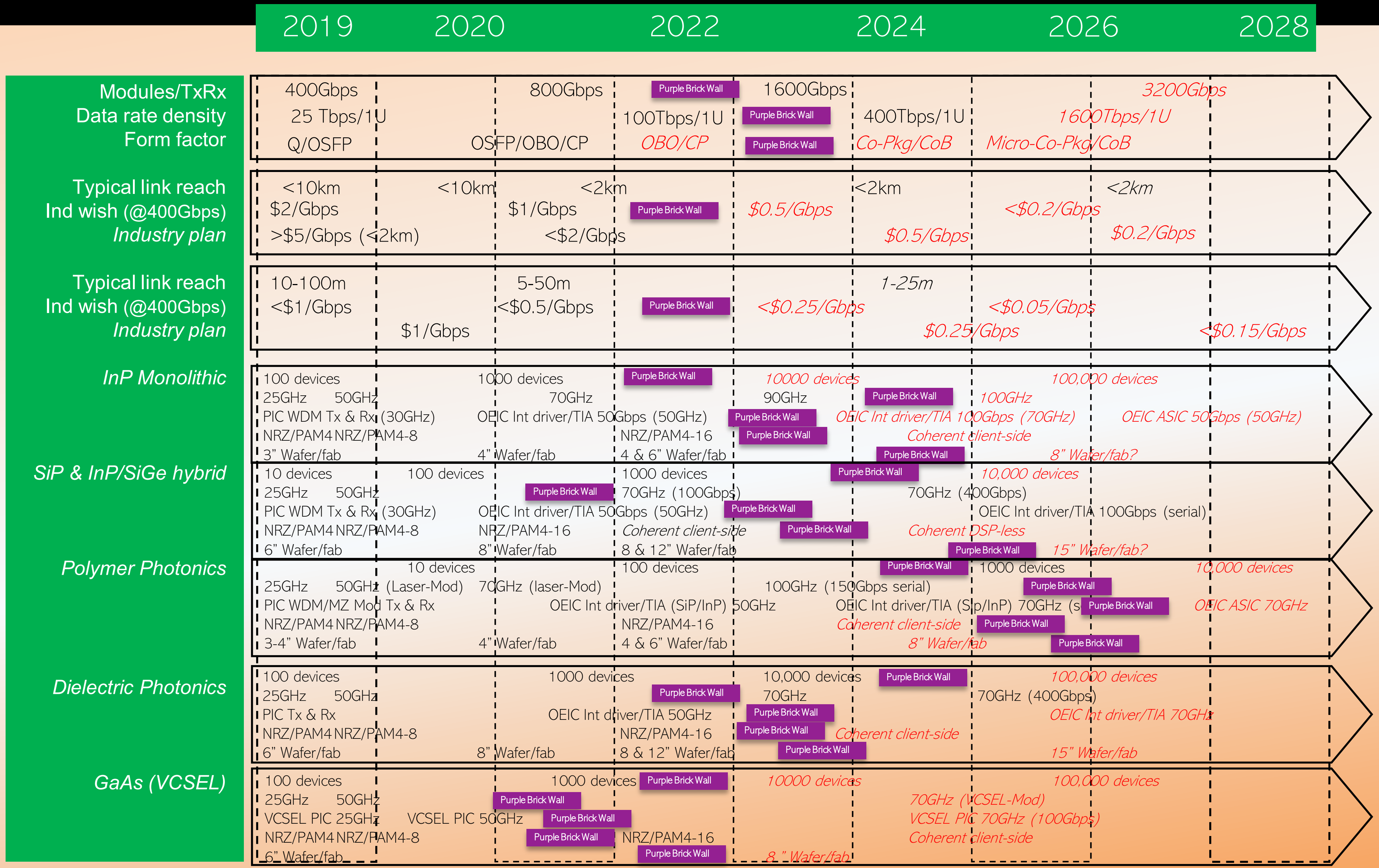
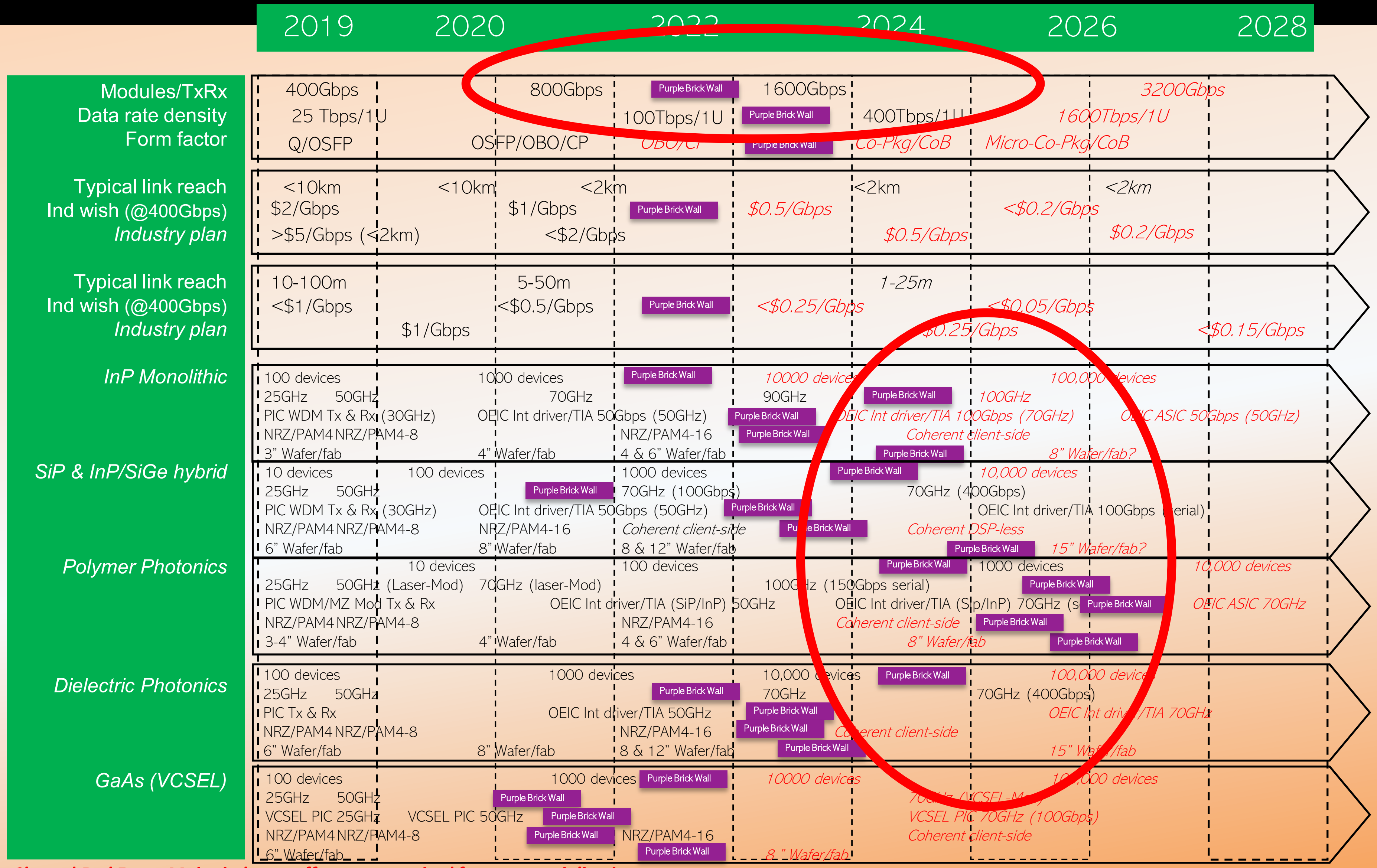
**Purple Brick Wall** = Technology cost barrier




***Slanted Red Font: Major industry efforts are required for commercialization***

**Source: Lightwave Logic**

# 800 and 1600Gbps; very high bandwidth 70GHz, co-packaging, low power, hybrid integration, low $/Gbps




***Slanted Red Font: Major industry efforts are required for commercialization***

**Source: Lightwave Logic**

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# Summary



*Fastest by Design*

# Electro-optic polymer example

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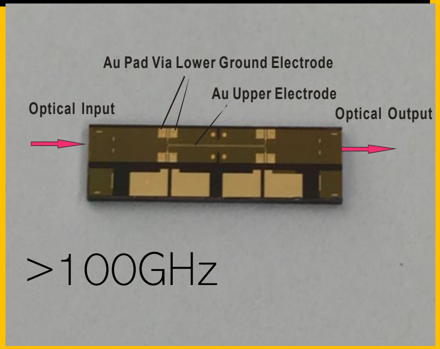
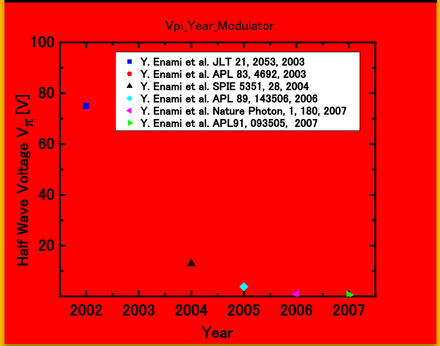
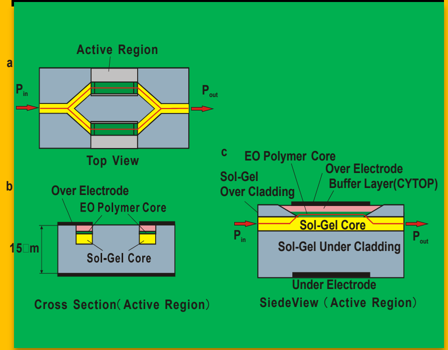
## Faster devices (100GHz+)




## Lower Power (Low voltage)




## Low cost (Easy fab)




## Robust (Stable)

| Test Item | Test Description | Specification: Method or Conditions | Sample Data | Passed Y/N |
|---|---|---|---|---|
| HTOL | High temperature operation life time test | Telcordia GR_468_COREi02 3.3.3.1; 2000 hrs at power, driver, bias and Ta = 85°C | 11 | Y |
| Low Temperature Storage | Storage only in low temperature | Telcordia GR_468_COREi02 3.3.2.1 -40°C, 72 Hour | 11 | Y |
| Mechanical Shock | Apply mechanical shocks to device | Telcordia GR_468_COREi02 3.3.1.1; mil-std-883 Method 2002.3 | 7 | Y |
| Vibration | Apply vibration to devices | GR_468_COREi02 3.3.1.1; mil-std-883 Method 2007.2. | 6 | Y |
| Thermal Shock | Sudden exposure to extreme changes in temperature | Telcordia GR_468_COREi02 3.3.1.2; mil-std-883 Method 1011.9. | 11 | Y |
| Fiber Twist | Twist fiber pigtail | Telcordia GR_468_COREi02 3.3.1.3.1; FOTP 36. | 8 | Y |
| Fiber Side Pull | Pull fiber pigtail | Telcordia GR_468_COREi02 3.3.1.3.2; GR-326-CORE 4.4.3.5. | 8 | Y |
| Cable Retention | Apply force to the cable | Telcordia GR_468_COREi02 3.3.1.3.3; FOTP 6. | 11 | Y |

Our EO polymers enable *radical innovation…*

# Summary

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- Speed today…
  - We as an industry are struggling with >50GHz analogue bandwidth. Higher speeds has to come from increasing complexity of modulation schemes and electronics
  - *We can use polymer modulators for 70GHz analogue bandwidth (for 100Gbps NRZ data, 200Gbaud PAM4 data)*
  - *E.g. 100Gbps single lane NRZ, 400Gbps with 4 lanes NRZ, 800 Gbps with 4 lanes PAM4*
- Power today… ✓
  - We as an industry are struggling to bring voltage levels at 70GHz down to 1Volt for any modulator design
  - *~1V means we can eliminate drivers, use direct drive from CMOS circuitry*
- Cost today… ✓
  - MZ modulators are expensive designs using InP, SiPh, $LiNbO_3$
  - *Spin-on fab compatible Polymer MZ fabrication is cost effective Mach-Zehnder fits in OSFP-like transceiver footprints*
  - *Hybrid integration possible with InP, Si photonics, etc.*
- Robust today… ✓
  - Industry expects standard Telcordia specifications for MZ modulators
  - *Polymers have achieved GR-468 and are continually improving their stability specifications*
- Roadmaps… ✓
  - Predictions have been fairly accurate to date…challenging times ahead

**Polymers are quickly becoming an important platform…**

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OTCQB: LWLG

# Thank you

## Symbol OTCQB: LWLG

# Many opportunities, however, all need robustness

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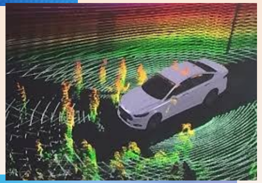
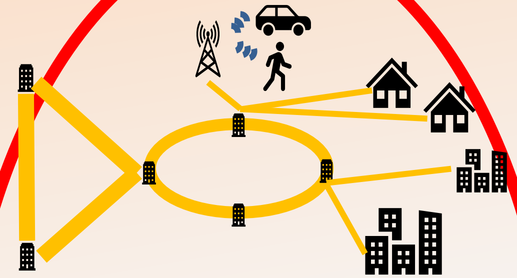
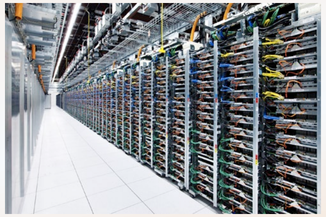
- 5G systems
- RF over fiber
- Automotive (LIDAR)
- Optical sensing
- Bio-photonic sensing
- Medical
- Instrumentation
- Others…



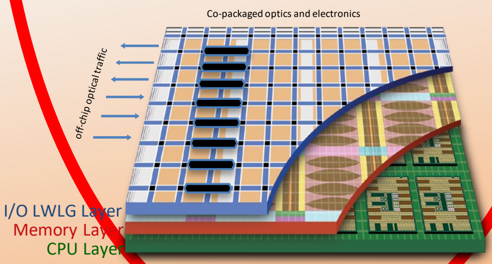




Telecommunications



Data communications




High performance computing

**Maturity (and robustness) in Fiber Comm enables other markets**

***Source: Mitsubishi Electric, Luxtera, IBM, Google***