

ADVANCES IN ELECTRO- OPTICAL COMPONENTS FOR DATA COMMUNICATIONS

05/09/2025

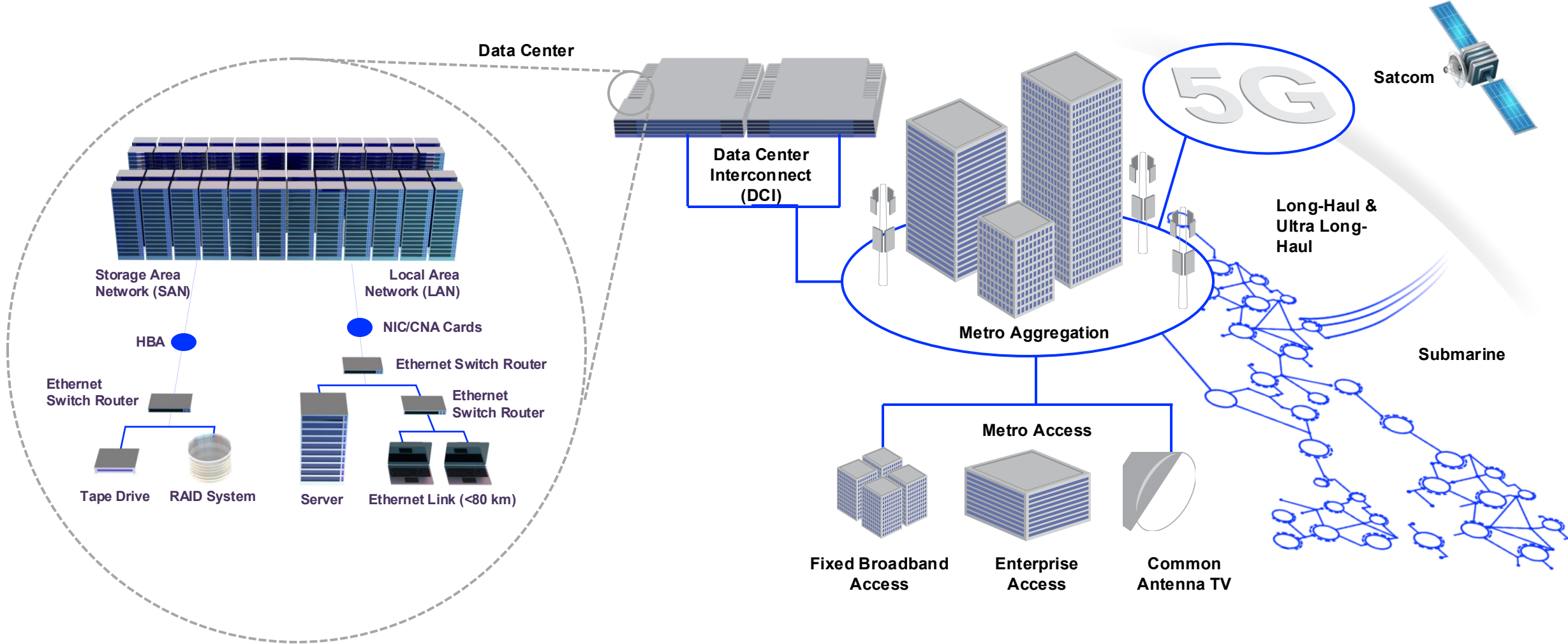
Jean Teissier, Laser Enterprise, Coherent

ARCHITECTURE

DATAKOM AND TELECOM DEFINITIONS

DATAKOM

TELECOM

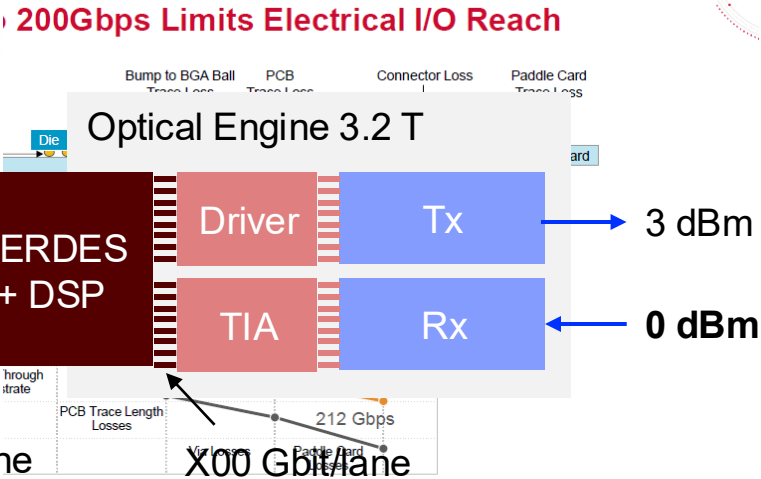
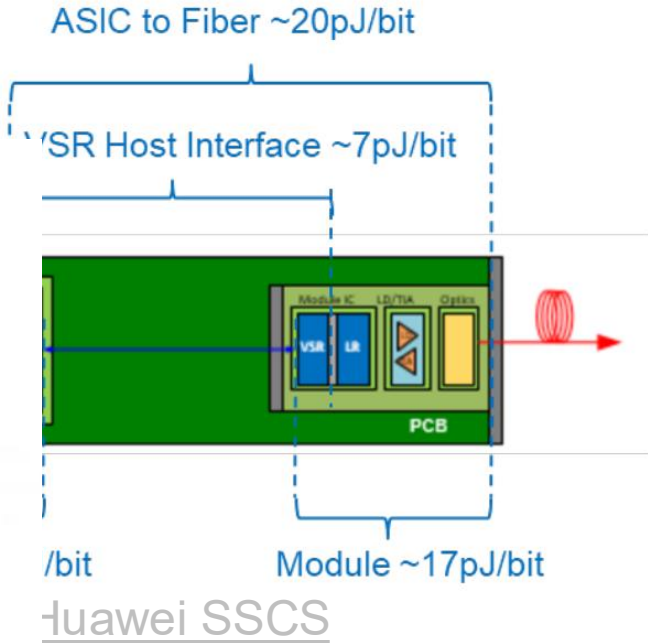


THE WORKHORSE: PLUGGABLE

- **Electronic**
 - XPU: ~ 5 Gbps NRZ
 - DSP/SERDES: ~ 200 pJ/bit
 - Copper traces/ Connector
- **Optics Module**
 - Pluggable DSP
 - Driver
 - Optical Engine
 - Photodiode
 - TIA
 - Pluggable DSP
- **Electronic**
 - Copper traces/ Connector
 - DSP/SERDES



Coherent





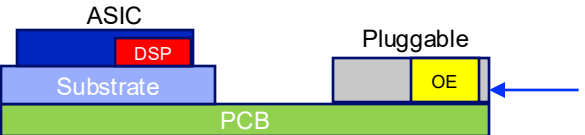
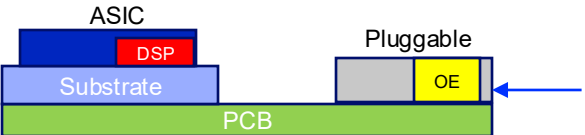





Advancement of Optical Interconnects Co-Packaged with ASIC

NEAR TERM TRANSCEIVER CONFIGURATION TRENDS

TRANSMIT RE-TIMED OPTICS (TRO) AND LINEAR PLUGGABLE OPTICS (LPO)

- New configurations driven by higher energy efficiency requirements
- TRO and LPO remove retiming to decrease overall system power consumption, latency, cost
- Removing retiming puts high linearity requirements on optics

| | Pluggable retimed | Transmit Re-timed Optics TRO | Linear Pluggable Optics LPO |
|--|---|---|---|
| TX |  |  |  |
| RX |  |  |  |
| Power consumption for 1.6T transceiver | 25W | 15W | 10W |
| DSP related Latency | ~100+ns | ~30+ ns | 0ns |
| Cost |  |  |  |

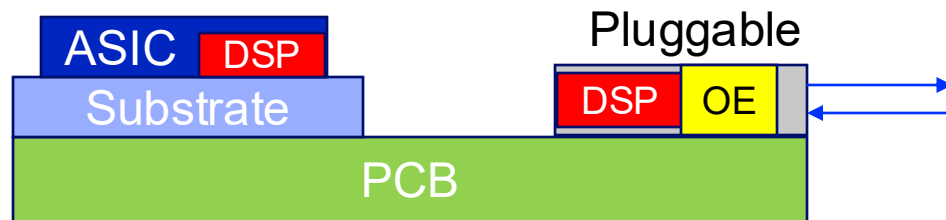
LONG TERM CONFIGURATION TRENDS

CO-PACKAGED OPTICS (CPO)

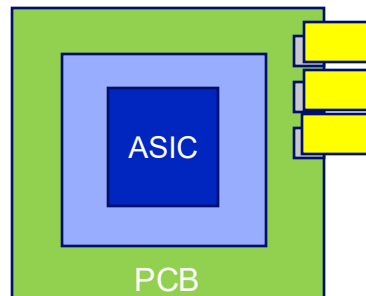
- Pluggable module gets replaced by “chipelets” surrounding host ASIC
- CPO helps to further reduce the power consumption and latency
 - Designed to connect terabits per second (Tbps) data among GPU/CPU/memory ASICs
 - Overcomes the distance limitations of copper wires, which are typically effective for 100-200Gbps lane rates
 - Limited by heat and energy constraints within the package, restricting optical interconnect distance
 - CPO architecture has very high reliability requirements due to the more difficult serviceability

Pluggable Optics

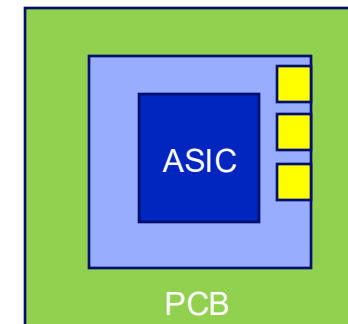
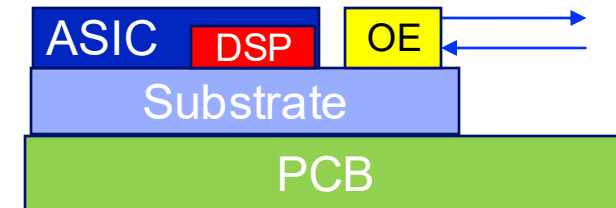
Side View



Top view



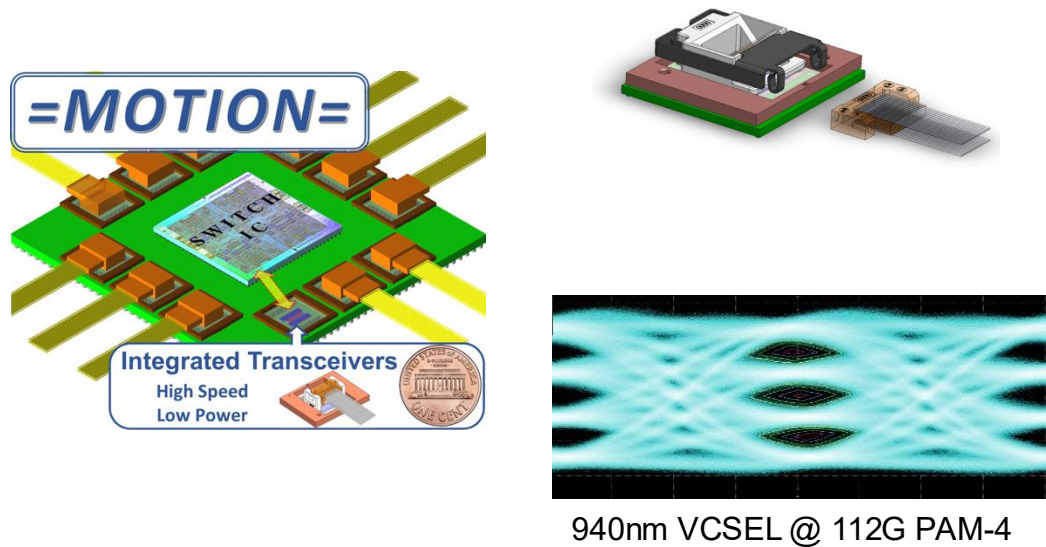
Co-Packaged Optics



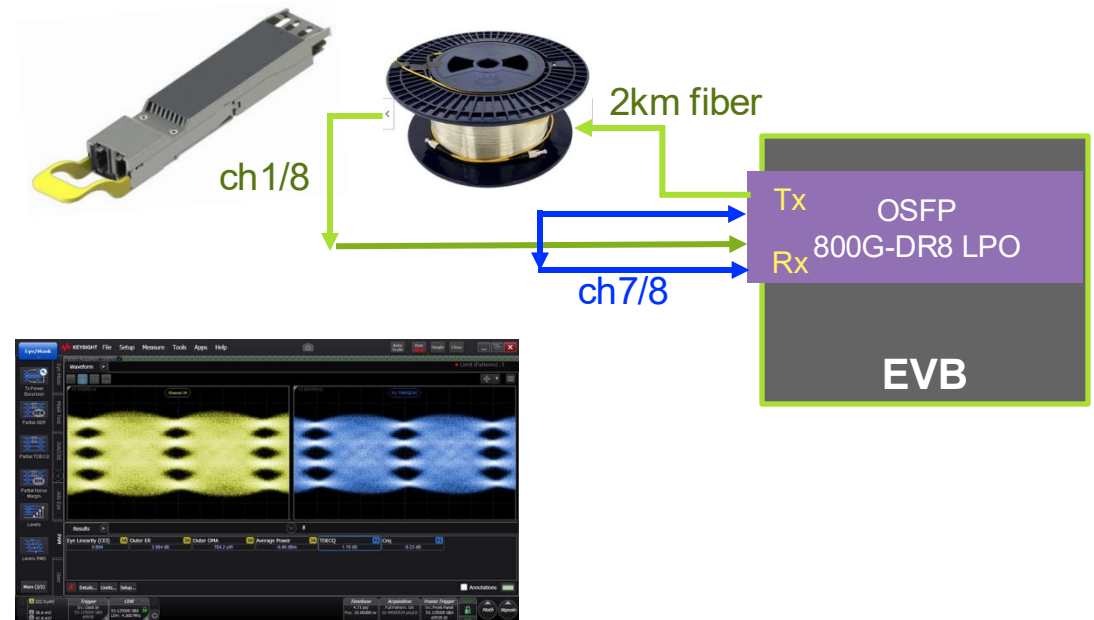
EXTENDIBILITY TO LINEAR, HALF-LINEAR, NEAR AND CO-PACKAGED OPTICS

- LPO, TRO, and CPO are packaging and architectural partitioning changes, as compared to traditional retimed pluggable optics
- Optical components in the packages are largely the same

Live demo of 800G VCSEL-based CPO at OFC 2023



Live demo of OSFP 800G-DR8 LPO at ECOC 2023



LASER TECHNOLOGIES AND MARKET

LASER TECHNOLOGIES FOR DATACOM AND TELECOM

| Datacom Short-Reach < 100 m | Datacom Mid- and Long-Reach 500 m to 10 km | Telecom 10 km ++ |
|---|--|--|
| 8x100G for 800G 16x100G for 1.6T 8x200G for 1.6T Gallium Arsenide • VCSEL | 8x100G for 800G 4x200G for 800G 8x200G for 1.6T 4x400G for 1.6T Indium Phosphide, Silicon Photonics • EML • Silicon Photonics • DFB-MZ | Coherent optics, multiple modulation formats (QPSK, QAM) Indium Phosphide, Silicon Photonics, Pockels • Narrow linewidth laser • IQ modulators • Coherent mixer and photodiode array |

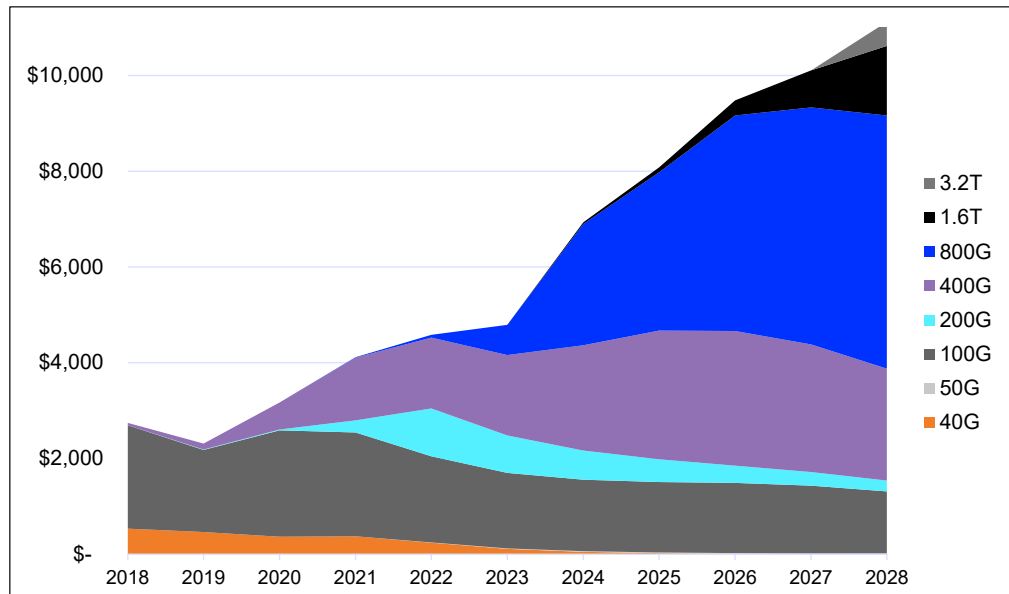
VCSEL: Vertical Cavity Surface-Emitting Laser
EML: Electro-Absorption Modulated Laser
CW: Continuous Wave
DFB-MZ: Distributed Feedback Laser with Mach-Zehnder Modulator
IQ: In-Phase/Quadrature

GROWTH DRIVERS FOR ELECTRO-OPTICAL COMPONENTS

DATACOM

- Datacom Growth Factors
 - AI/ML for Datacenters
 - Expansion of cloud services and applications
 - Need for enhanced network cybersecurity
 - Expect 800G/1.6T to dominate for next 5 years

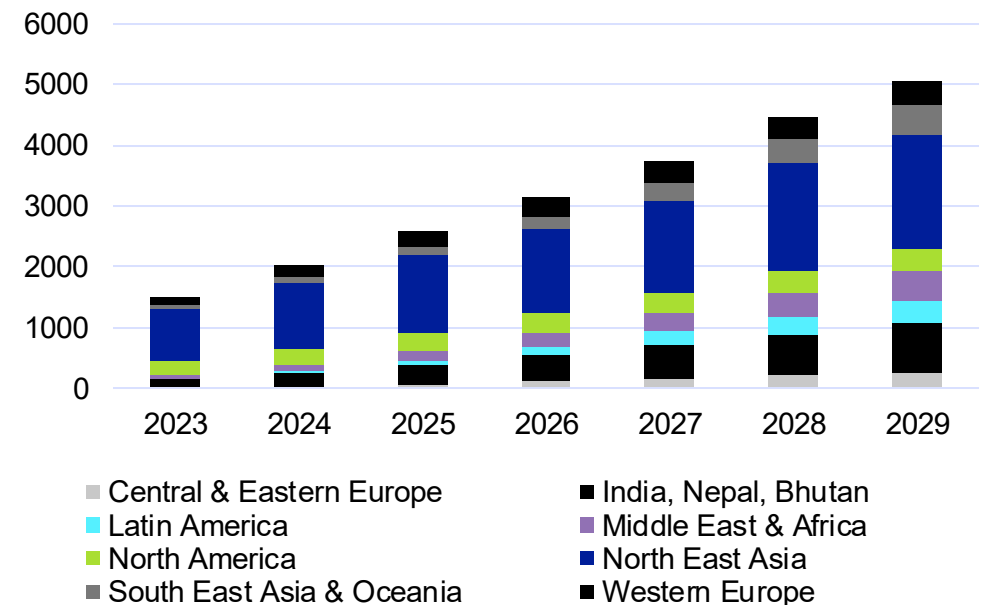
Datacom Transceiver Global Market



TELECOM

- Telecom Growth Factors
 - 2.6 billion people not connected to the internet
 - 5G growth in developing economies & 6G emergence
 - Increasing internet demand in remote and rural areas
 - Growth of Internet of Things (IoT) devices

5G Mobile subscriptions



DATAKOM MARKET OVERVIEW:

- **AI is driving a speed increase:**

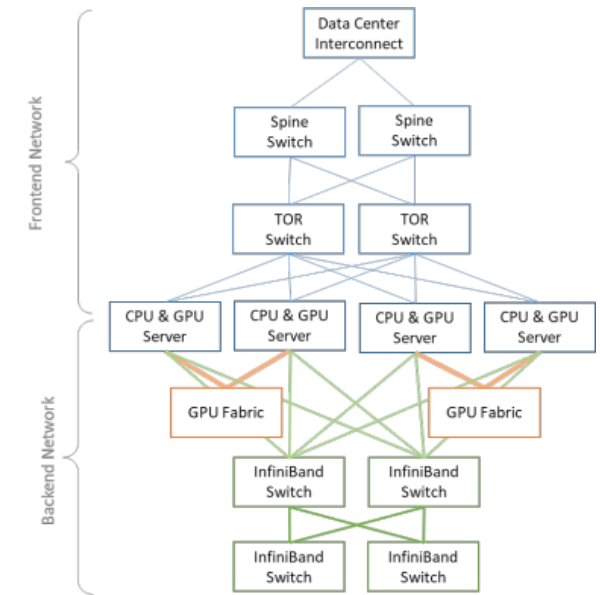
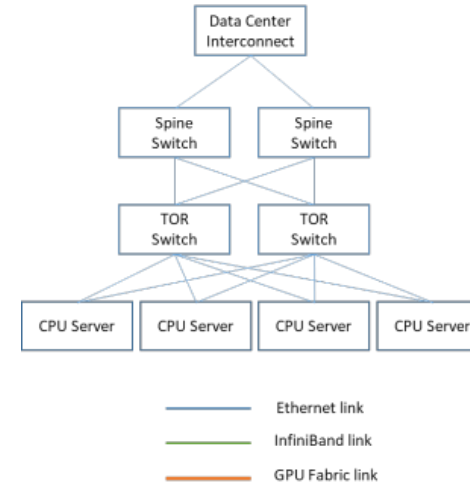
- New market: Datacenter “Back End”
Latency and pJ/bit are key

- **Move toward Co-Packaged Optics**

- Pluggable density
- Power consumption at high bitrate
- Lower latency

- **Markets**

- **Scale-up:** Short reach all to all interconnect
 - Length < 30 m
- **Scale-out:** (Infinity-band and “Ultra Ethernet”)
 - > 30 m – 2 km for IMDD
 - First CPO for **scale-out**, from ASICS to ASICS (Switch to Switch)



Credit: Sujal Das

Scale Out: SiPh CPO!



SiP CPO @ 200 G/lane

Credit: NVIDIA

OPTICAL COMPONENTS

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VCSEL: Vertical Cavity Surface-Emitting Laser
EML: Electro-Absorption Modulated Laser
CW: Continuous Wave
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TRENDS IN GaAs VCSELS FOR COMMUNICATIONS

▪ GaAs VCSELS

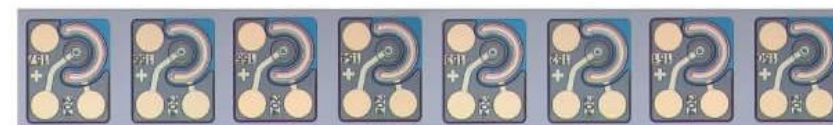
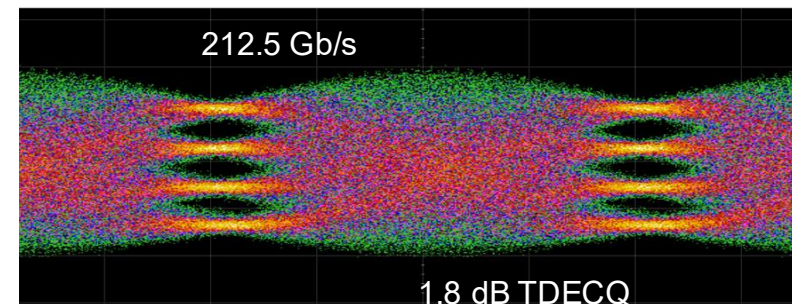
- Lowest cost
- Highest energy efficiency for short reaches up to 50/100m.
- Best path for parallelization

▪ 100G PAM-4 VCSELS are shipping in production

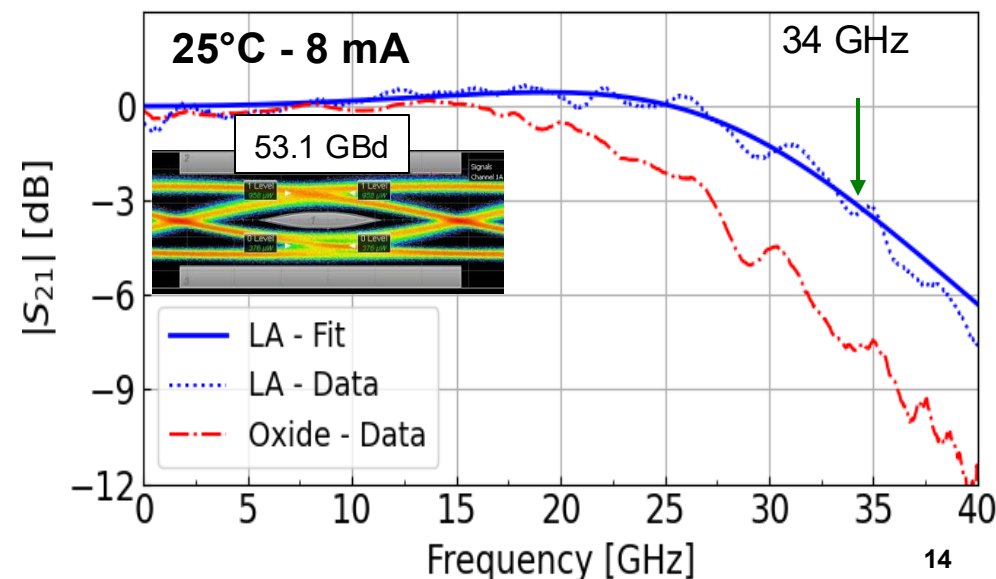
- 1x4 and 1x8 arrays support 400G and 800G transceivers
- Supporting Ethernet, Fibre Channel, Infiniband, and proprietary links such as NVLink
- Key specifications: Bandwidth, crosstalk, RIN Noise

▪ Path to 200G/lane VCSELS

- Demonstration link at 200G/lane was presented at OFC2025
- Lithographic Aperture VCSELS Have the Potential to Achieve the Long Lifetimes Required by Datacom Applications and well controlled small apertures
- Work improvement on RIN and bandwidth optimization ongoing



VCSEL Technologies Compared
4 μm apertures



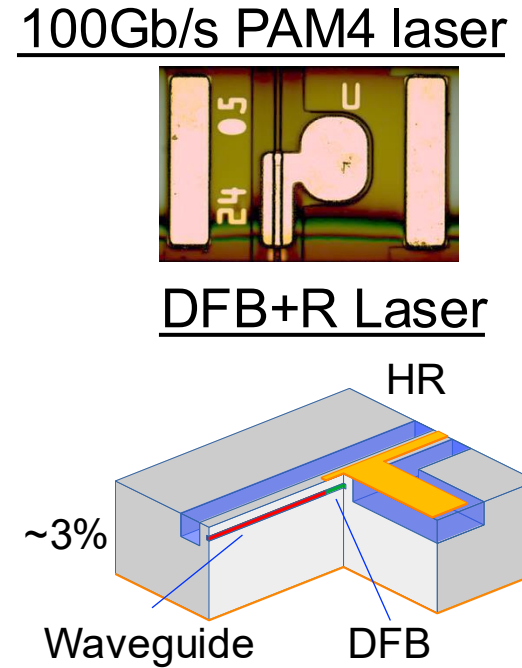
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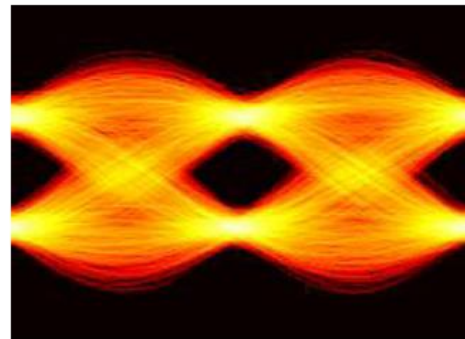
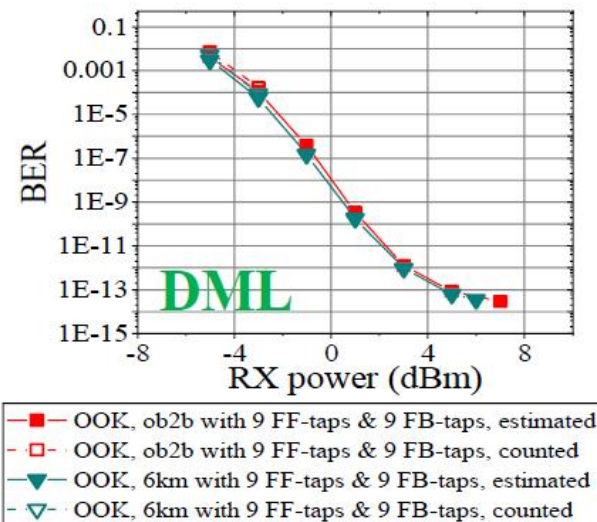
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EML: Electro-Absorption Modulated Laser
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DFB-MZ: Distributed Feedback Laser with Mach-Zehnder Modulator
IQ: In-Phase/Quadrature

HOW FAR CAN WE PUSH DIRECTLY-MODULATED INP LASERS?

- **InP Directly Modulated Laser (DML) is low cost and low power for <10 km**
 - 100Gb/s PAM4 for DR4, DR8, and FR4 demonstrated, can be operated uncooled
 - 50Gb/s NRZ with high output power for 50G PON
- **Demonstrated 106.25 G NRZ and 212G PAM4 over 6 km with DFB+R Laser**
 - DFB+R laser is a DFB laser with passive waveguide and 3% front facet coating, creating strong etalon ripples that excite Photon-Photon Resonance effect
 - Demonstrated 75 GHz bandwidth at 25°C and 62 GHz at 50°C
 - 6km transmission demonstrated at 106G NRZ and 212G PAM4 with simple Rx (9 FF, 9 FB taps)

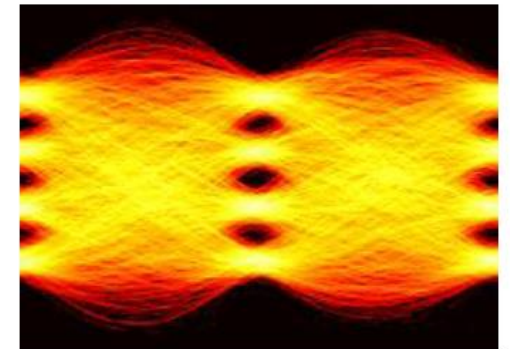
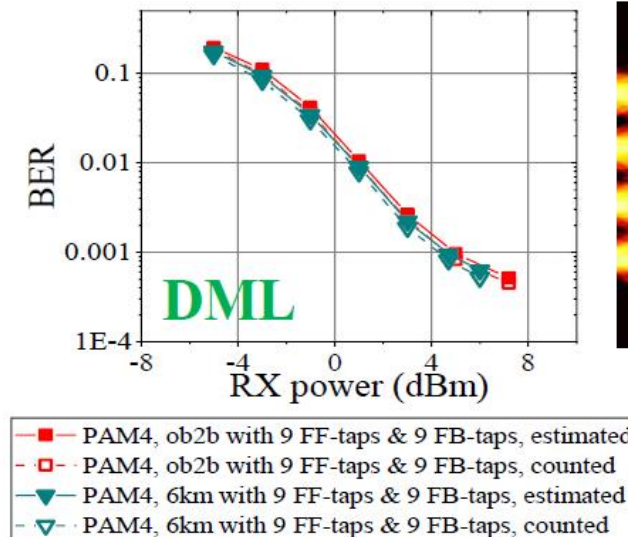


106.25 Gbaud OOK, 6km



106.25 Gbaud OOK
with DML, 6km

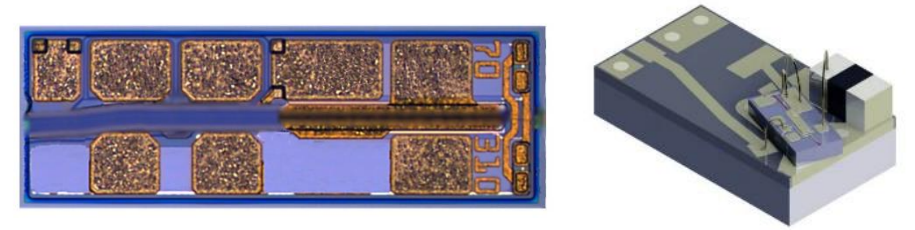
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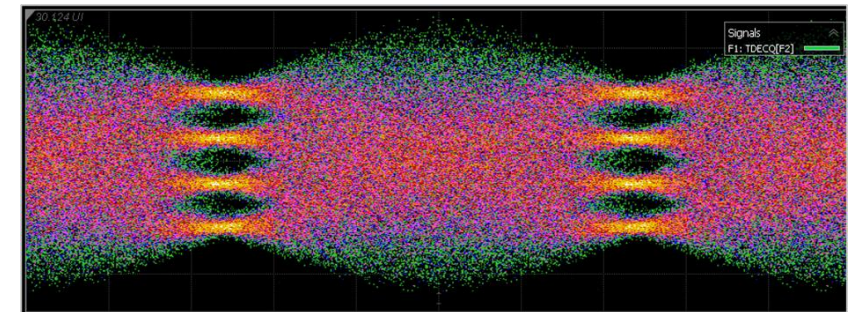
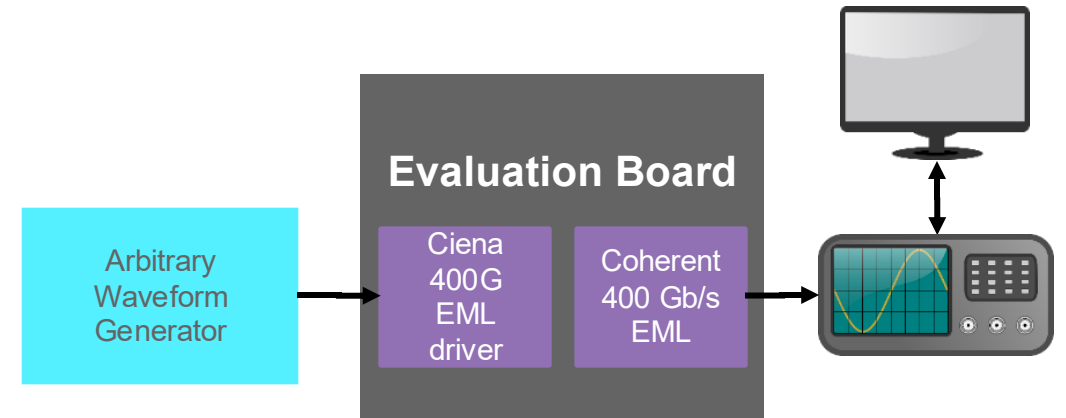
EMLs: 200 Gb/s TO 400 Gb/s TRANSMISSION

- **InP Electro-Absorption Modulated Lasers (EMLs) are used for 200G/lane today**
 - High EO BW
 - Compact size
 - InP has better electro-optic performance than SiP
 - Mature platform
- **Demonstration of 400G/lane**
 - Monolithically integrated O-band DFB laser and an electro-absorption modulator
 - Supporting 400 GBps PAM4 modulation
 - Optical power 5 dBm, ER 4.7 dB, low noise 147 dB/Hz
 - Compatible with cost-effective non-hermetic packaging
 - Integrated on-chip RF termination for improved signal integrity



Coherent EML

Coherent EML on CoC



400G PAM4 Optical Eye @OFC2025

SILICON PHOTONICS FOR 100G/LANE AND 200G/LANE

■ Silicon Photonics

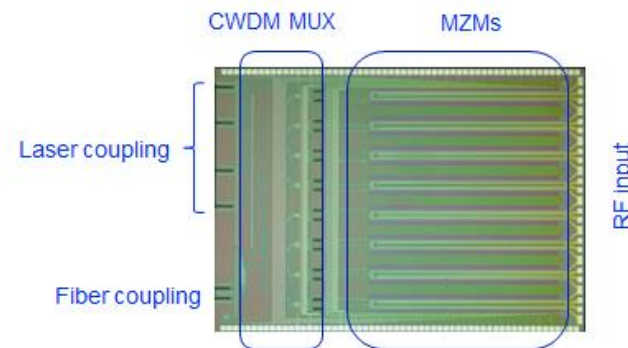
- Silicon photonics can reduce module cost and complexity by fewer lasers and integration of passives
- New platform
- Architecture for each module determined based on detailed specs for application

■ >70GHz Silicon Mach Zehnder Modulators and Ge-based photodiodes demonstrated

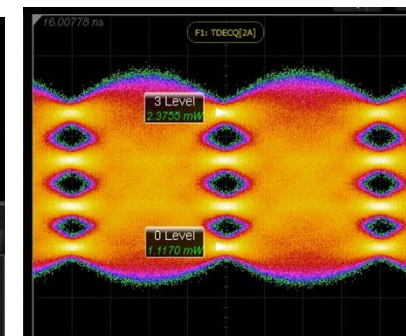
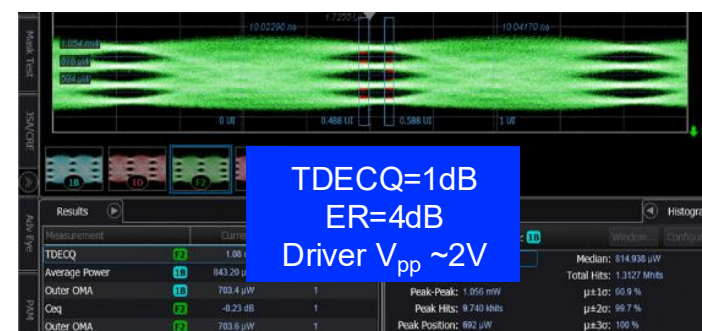
- 800G 2xFR4, TDECQ 1 dB based on Si MZM

■ Demonstration of 200G/lane

- 224 Gb/s PAM4 eyes demonstrated, <1 dB TDECQ
- SiPh requires high power InP CW laser
 - 100 mW uncooled and 200 mW cooled
 - 1310nm for DR4 and DR8, CWDM4 for FR4 and 2xFR4



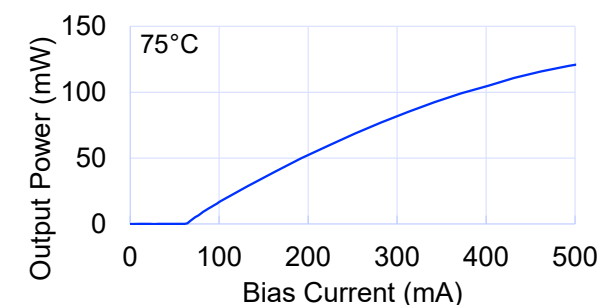
Silicon Photonics IC



Modulation diagram from 800G 2xFR4 transmitter 224 Gb/s PAM4 optical eye

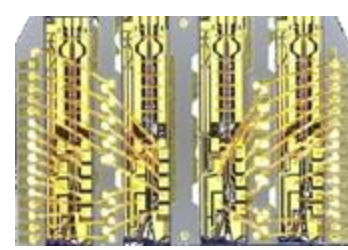
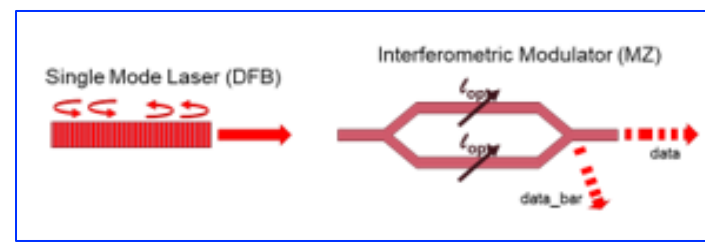


100 mW Laser



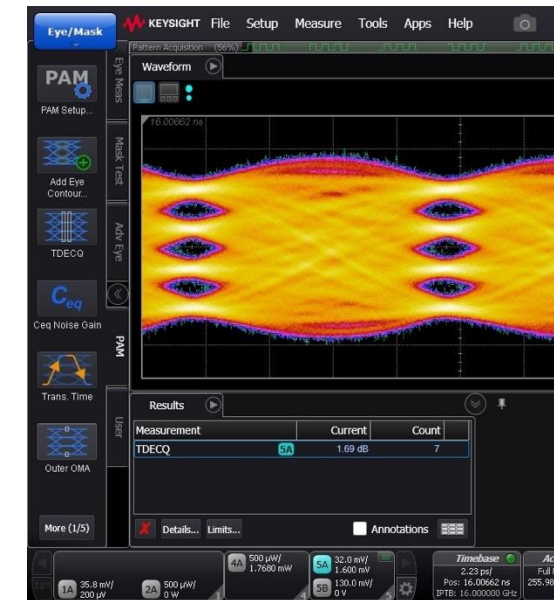
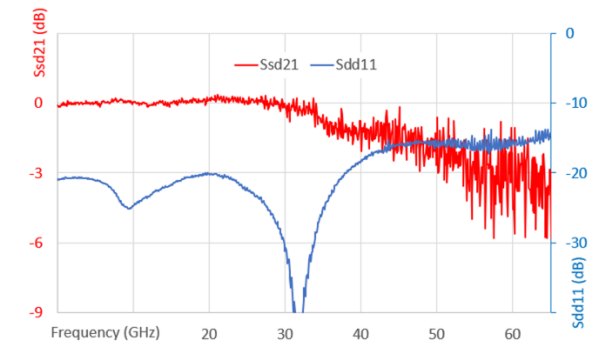
200Gb/s DFB-MZ

A HIGH PERFORMANCE ALTERNATIVE TO EML



Coherent DMZ CoC, 4ch

- **InP CW Laser with Integrated Mach-Zehnder Modulator**
 - Differential drive is used for superior signal integrity and reduced cross-talk
 - Uncooled operation enabled
 - Linear performance is a great fit for Linear Pluggable Optics (LPO)
 - Channel-specific positive and negative chirp control for dispersion management
 - Supports 800G and 1.6T at 10 km
 - Cooled LAN-WDM for 10 km, uncooled CWDM for shorter links
- **Demonstrated 200Gbps performance**
 - High performance: 8.5 dBm output power, 7 dB OMA, -147 dB/Hz noise, low TDECQ
 - Live demo of DFB-MZ over 6 km optical fiber and 800G FR4 OSFP over 3 km fiber at ECOC 2023



Live demo of 800G FR4 OSFP with DFB-MZ
at ECOC 2023: 200G PAM4 Optical Eye 19

LASER TECHNOLOGIES FOR DATACOM AND TELECOM

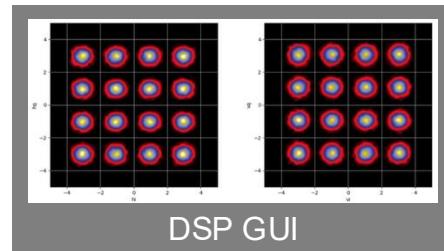
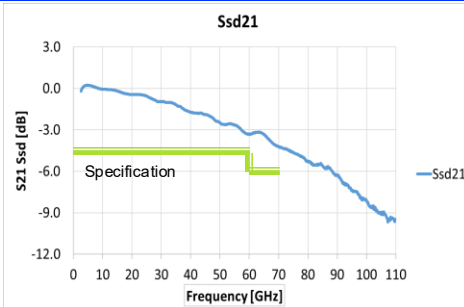
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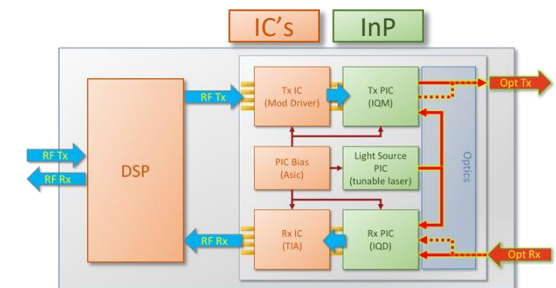
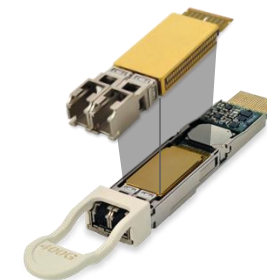
InP PHOTONIC INTEGRATED CIRCUITS (PICs) FOR COHERENT OPTICS TRANSCEIVERS

- **InP PIC has best electro-optic performance, good fit for coherent transceivers**
 - Especially for high optical output power, long reach such as 400G and 800G Metro and Long-Haul
- **Integrated InP PICs demonstrated:**
 - Wavelength-tunable narrow-linewidth laser, semiconductor optical amplifiers, IQ modulators, coherent mixer, photodiode array.
- **Advantages of InP**
 - Bandwidth to support >200 Gbaud modulation
 - Low insertion loss and low drive voltage yields lower power dissipation
 - Integrated semiconductor optical amplifiers deliver high Tx output power (>0dBm)
 - InP dual polarization coherent mixer and photodiode array provide higher bandwidth, improved Rx sensitivity

Live demo of **800G** coherent transmission
with **140 Gbaud IC-TROSA** at ECOC 2023

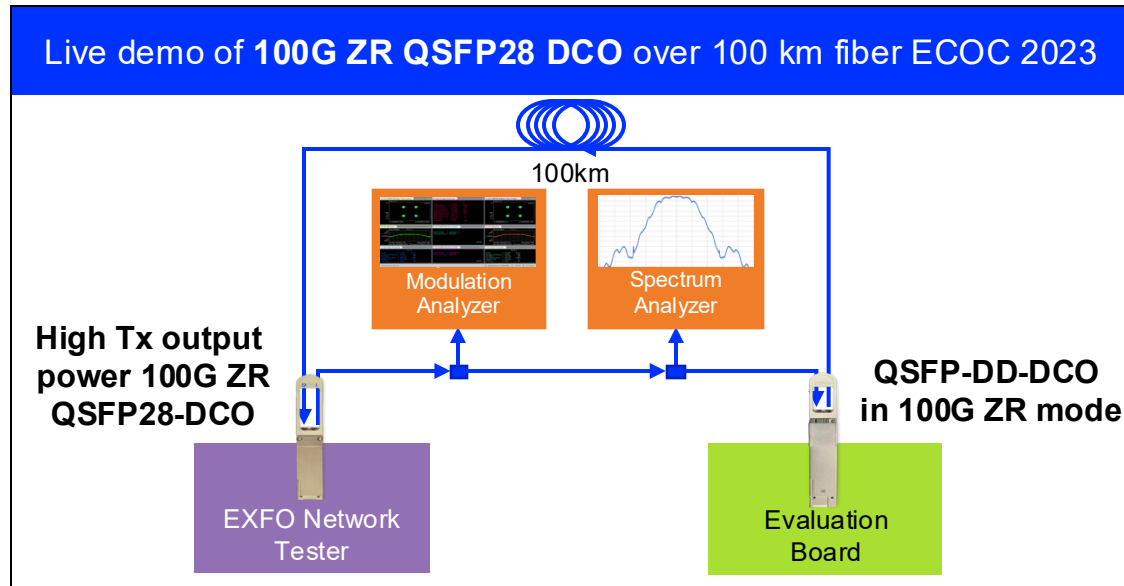


Live demo of **400G QSFP-DD DCO**
over 75 km and 430 km (with amplifiers) at ECOC 2023

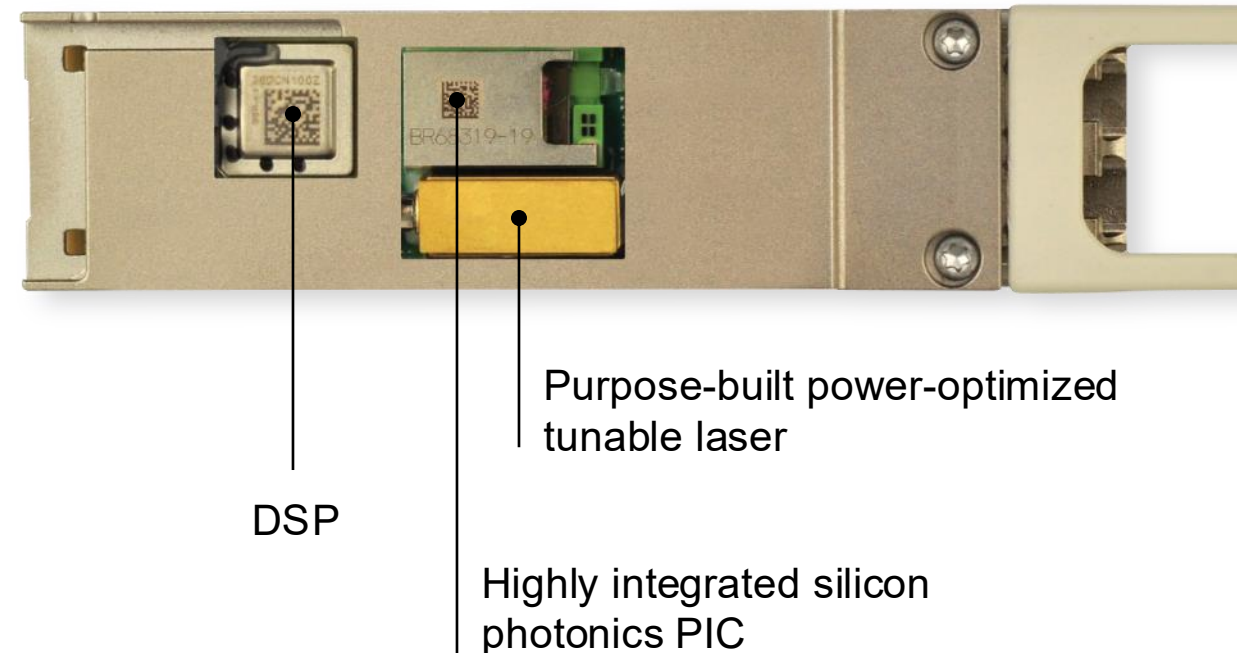


SILICON PHOTONICS FOR COHERENT OPTICS TRANSCEIVERS

- Silicon Photonics provides low-cost integration of passives
- For applications where electro-optic performance is sufficient, silicon photonics can enable a lower cost and more compact module such as Coherent's 100GZR QSFP28 DCO
- Requires low linewidth InP tunable laser



100ZR QSFP28 DCO



BEYOND 200GBPS NEW MODULATOR TECHNOLOGIES

MATERIALS FOR HIGH BANDWIDTH MODULATORS

- **LNO (Lithium Niobate)**
 - Utilizes the electro-optic effect in lithium niobate crystals to modulate light, known for high optical quality and broad transparency range; uses Pockels effect for refractive index variation
- **BTO (Barium Titanate)**
 - Employs barium titanate to modulate light, offering strong electro-optic effects; high efficiency Pockels effect
- **InP (Indium Phosphide)**
 - Based on semiconductor indium phosphide, efficient at absorbing and emitting light and allows integration of electronic and optical components; supports both EAM and MZM
- **SiP (Silicon Photonics)**
 - Uses the electro-optic properties of silicon within photonic circuits, compatible with silicon-based electronics manufacturing processes; free-carrier plasma dispersion effect used instead for refractive index variation
- **SOH (Silicon-Organic Hybrid)**
 - Combines silicon structures with organic electro-optic materials to enhance modulation efficiency
- **POH (Plasmonic-Organic Hybrid)**
 - Integrates plasmonic structures with organic materials to achieve high-speed light modulation at very small scales

HIGHER BANDWIDTHS MODULATOR TECHNOLOGIES

- **Multiple materials support high bandwidth EO modulators**
 - Highest bandwidth measured for Plasmonic-Organic Hybrid modulators (997 GHz)
 - Other materials are all capable of high BW of at least 100GHz
- **Other important parameters to consider**
 - Loss, form factor and efficiency ($V_{\pi} \cdot L$), energy consumption, reliability, compatibility with silicon/InP fab, maturity

| Modulator Material | Modulator Type | Reported BW | Band | Data rate/ Lambda | Voltage | Reference |
|--------------------|----------------------|-------------|------|-------------------|---------|-----------|
| TFLN 1310 | MZM | 108 GHz | O | 224GBd | 1 Vpp | 1 |
| InP | MZM IQ | 100 GHz | C | 192GBd | 1.1Vppd | 2 |
| BTO 1310 | MZM | 70 GHz | C | 256GBd | 1.9V | 3 |
| SOH 1310 | MZM | 80 GHz | O | 192GBd | 0.92V | 4 |
| Silicon | Microring | 67 GHz | C | 100Gbd | 0.8 | 5 |
| Silicon | Slow light modulator | 110GHz | C | - | 4V | 6 |
| POH | MZM, IQ | 997GHz | C | 256GBd | 0.8V | 7 |

[1] Xiangyu Meng et al “High Performance Thin-film Lithium Niobate Modulator Applied ITO Composite Electrode with Modulation Efficiency of $1V \cdot cm$ ” <https://arxiv.org/pdf/2311.05119>

[2] H. Wakita et al. “100-GHz-bandwidth InP-based On-board Coherent Tx Front-end enabling 2-Tb/s/λ Optical Transmission,” in *Optical Fiber Communication Conference (OFC) 2024*, Technical Digest Series (Optica Publishing Group, 2024), paper Th4C.2.

[3] Kohli, Manuel et al. (2024). 256 GBd Barium-Titanate-on-SiN Mach-Zehnder Modulator. M3K.5. 10.1364/OFC.2024.M3K.5.

[4] A. Schwarzenberger et al. “O-Band SOH Mach-Zehnder Modulator Operating at a PAM4 Line Rate of 384 Gbit/s with Sub-Volt Drive Voltage,” in *Optical Fiber Communication Conference (OFC) 2024*, Technical Digest Series (Optica Publishing Group, 2024), paper Th4B.6

[5] Zhang et al. “200 Gbit/s Optical PAM4 Modulation Based on Silicon Microring Modulator.” 2020 European Conference on Optical Communications (ECOC) (2020): 1-4.

[6] C. Han et al. “Ultra-compact silicon modulator with 110 GHz bandwidth,” in *Optical Fiber Communication Conference (OFC) 2022*, S. Matsuo, D. Plant, J. Shan Wey, C. Fludger, R. Ryf, and D. Simeonidou, eds., Technical Digest Series (Optica Publishing Group, 2022), paper Th4C.5.

[7] 22. M. Burla et al. “500 GHz plasmonic Mach-Zehnder modulator enabling sub-THz microwave photonics,” APL Photonics 4(5), 056106 (2019).

RX

PHOTODIODES FOR 100G/LANE AND 200G/LANE

■ GaAs PDs

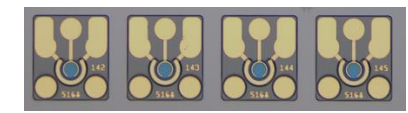
- >28 GHz bandwidth at -2V with 32 μ m aperture diameter for 56Gb/s data transmission
- High responsivity of 0.6 A/W; very low dark current of 3 pA

■ InGaAs/InP PDs

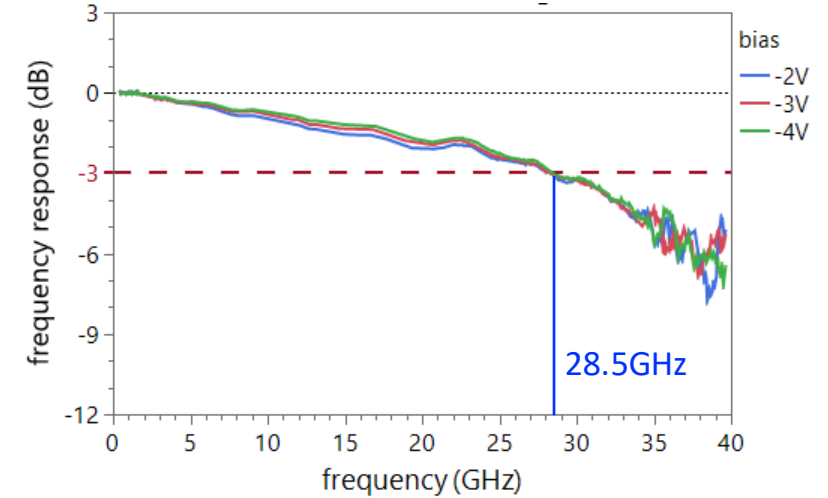
- 100 Gb/s PAM4 PIN PD in high-volume production
 - Responsivity at 1310 nm > 0.8 A/W, capacitance < 80 fF
- 200 Gb/s PAM4 PIN PD in sampling stage
 - Back-illuminated flip-chip bonded photodiode with effective optical aperture diameter of 20 μ m
 - Responsivity at 1310 nm > 0.66 A/W, capacitance < 50 fF, -3dB BW > 50 GHz

■ Ge-based PDs in Silicon Photonics

- 0.7 A/W demonstrated



GaAs PDs



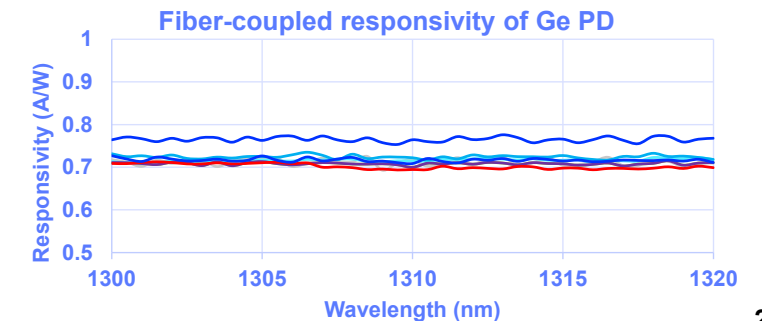
InGaAs/InP PDs



4x100G



4x200G



SUMMARY

SUMMARY

- **Significant advances have been made in optical components for datacommunications**
- **Communications:**
 - VCSELs, DFBs, EMLs, DFB-MZ, and Silicon Photonics to support 200G/lane are here
 - 400G/lane here or in progress
 - Will support pluggable transceivers up to 6.4T
 - Similar components used for near- or co-packaging
 - Pace of development is accelerating while challenges are getting greater

COHERENT

OPTICAL COMPONENTS FOR SENSING

TRENDS IN SENSING

- **3D Sensing: Anything 2D image application that would benefit from depth information**
- **It's not just 3D Sensing anymore:**
 - Proximity sensing, skin sensing, eye tracking, materials sensing, food/environmental sensing, bio/health sensing

Gaming/Virtual/Augmented Reality



People authentication
(access/crime)



Driver monitoring



Occupancy monitoring



Enhanced cameras,
collision avoidance



Facial biometrics
in cell phones



Proximity sensing
in earbuds



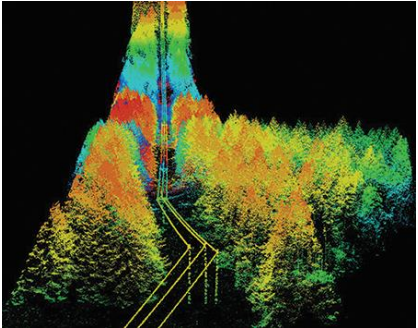
Gesture-Enhanced Gaming



Robot Vision in Factories



Vegetation mapping
for fire prevention



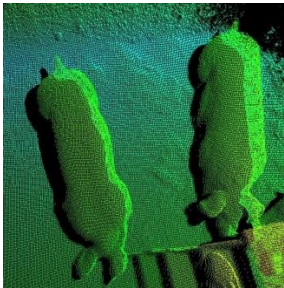
Industrial



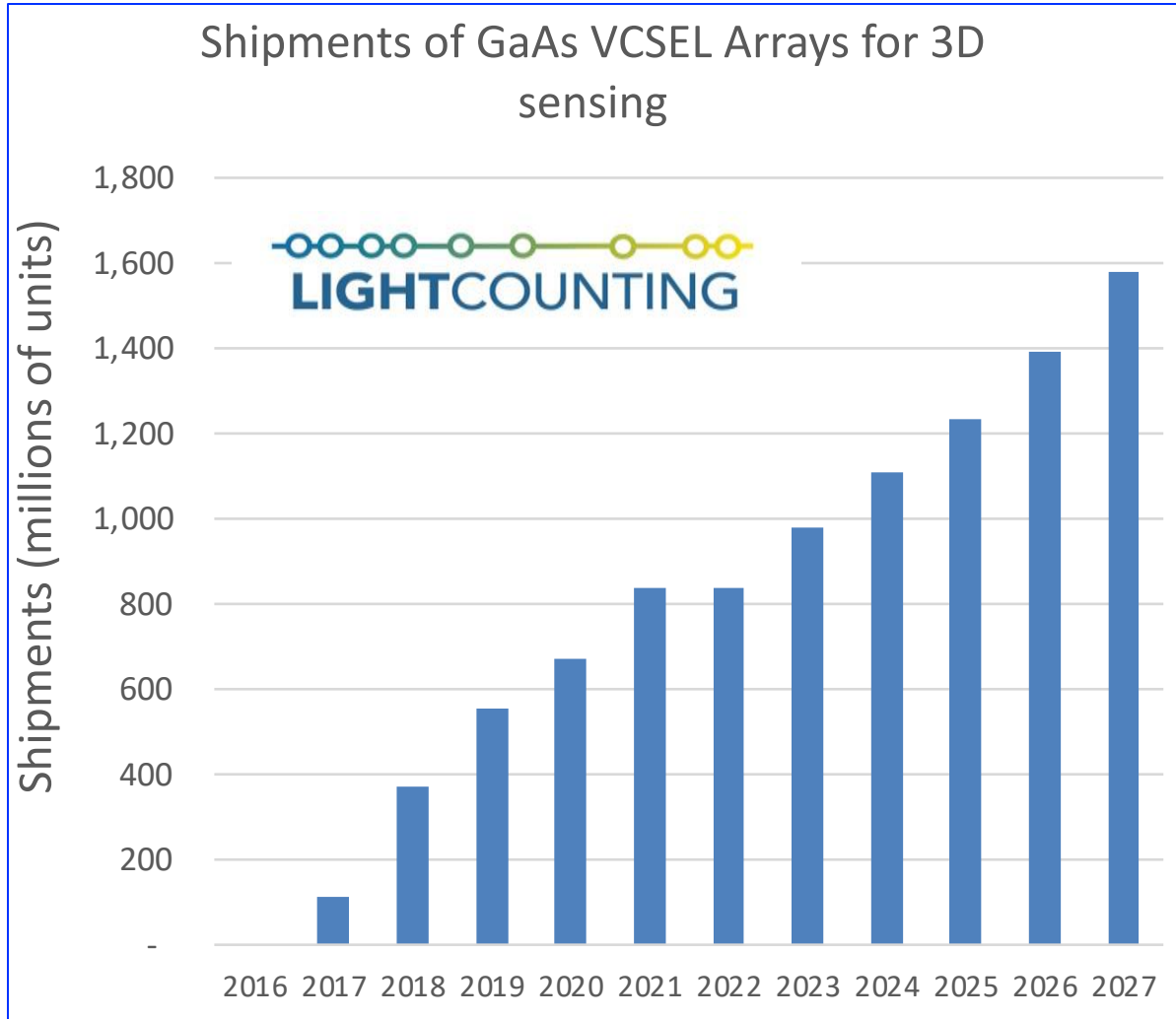
Warehouse
robots



Agriculture



SENSING IS A HIGH-VOLUME MARKET FOR GaAs VCSELS



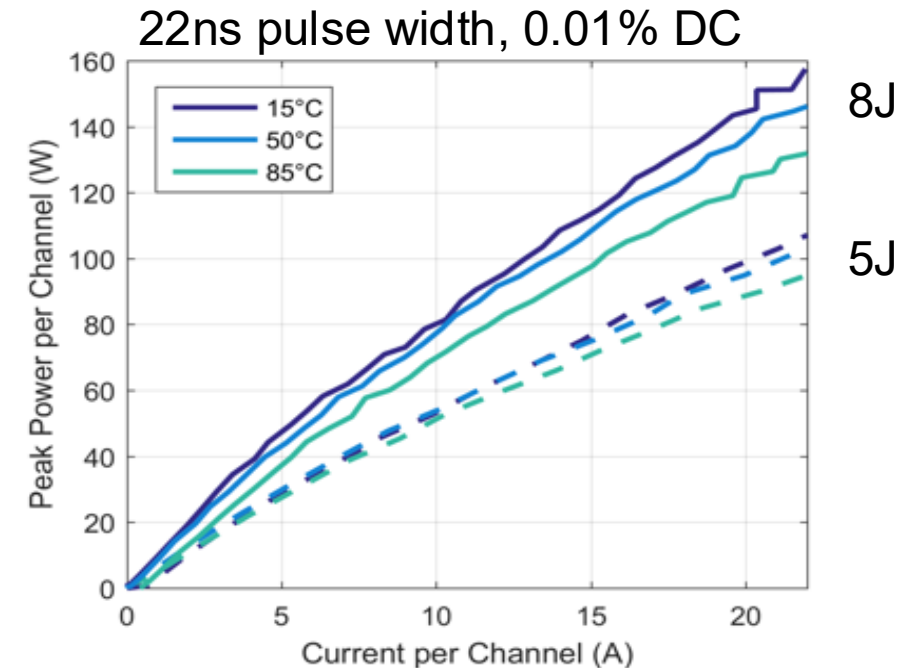
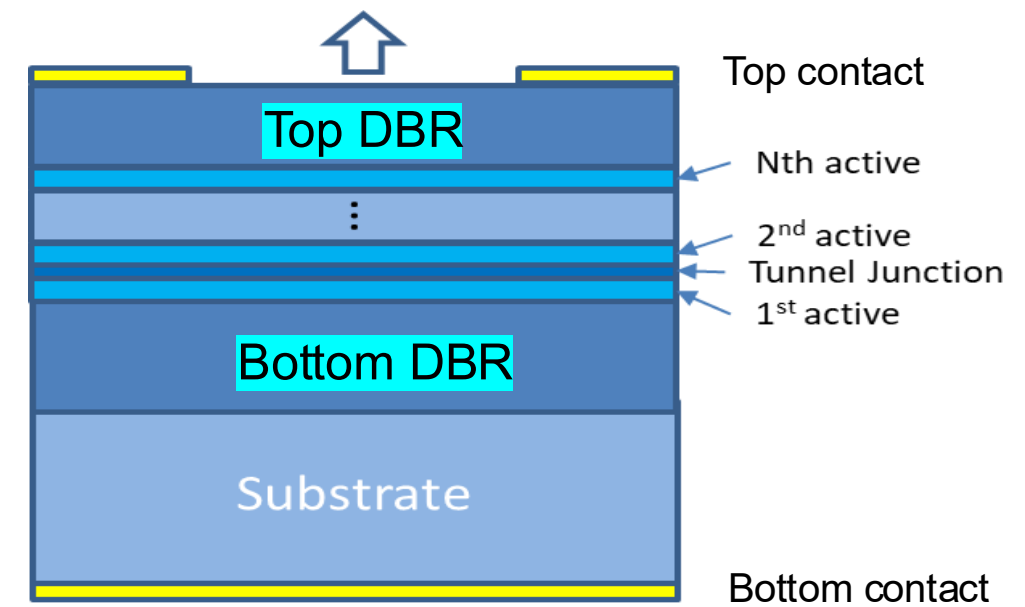
- Sensing VCSEL die volume significantly higher than Datacom
 - Most die are 2D arrays up to 300 elements
 - 99% of all VCSEL emitters shipped are for Sensing
- Coherent has shipped over 100B VCSEL emitters
 - 6" GaAs VCSEL manufacturing in U.S. and Europe – epi, fab, test all in-house

Coherent VCSEL fab in Sherman Texas



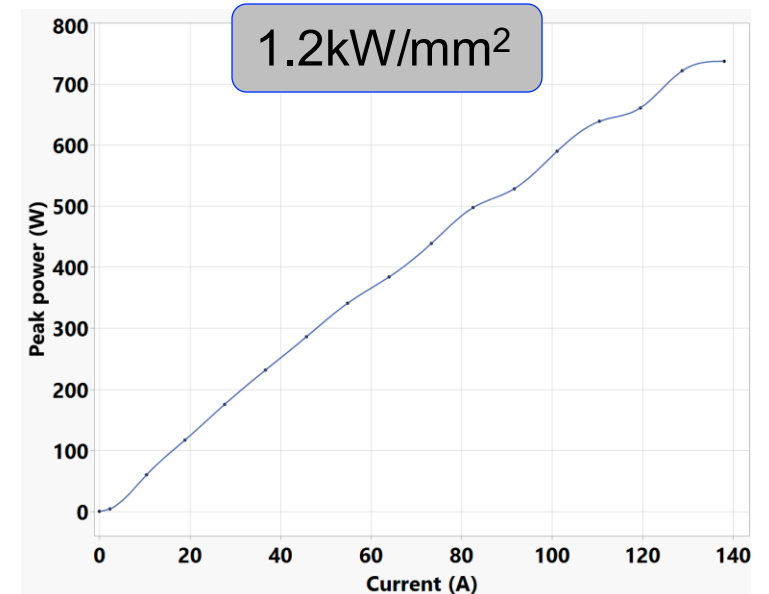
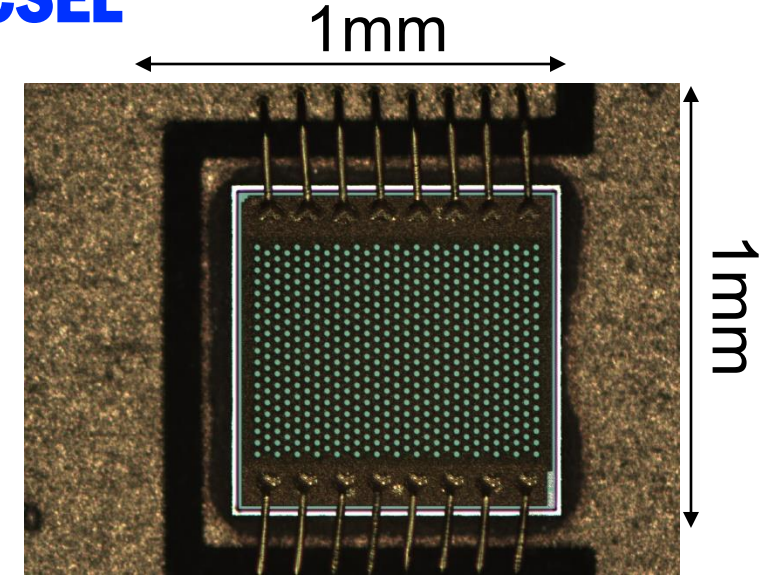
MULTI-JUNCTION VCSELS

- **Vertical stacking of active regions using a tunnel junction**
- **Advantages**
 - Higher power density, smaller chip, lower cost
 - Lower current enables simpler Laser Driver, low EMI, faster rise and fall times
 - Higher slope efficiency and Power Conversion Efficiency
 - VCSELS demonstrated up to 9 junctions
- **Limitations**
 - Thermal performance; mainly used in short-pulse applications
 - Higher voltage drivers required
- **Multi-junction VCSELS are shipping in production today**



HIGH OPTICAL POWER GENERATED BY MULTI-JUNCTION VCSEL

- Chip
 - Size : 1mm²
 - 500+ emitters
 - 9 junctions
- Electro-Optic performance
 - > 700W, limited by Eval board, demonstrated at DC < 0.01%, 3ns pulse
 - > 1.2kW/mm²



3D SENSING VCSEL OPTICS AND PACKAGING

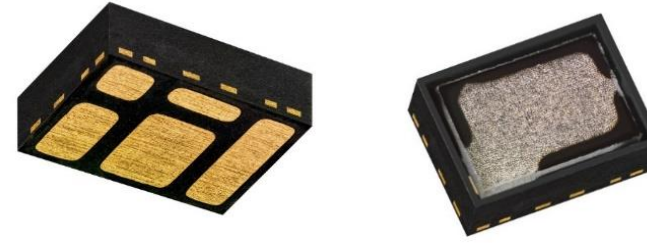
■ Co-design of VCSEL with optics

- Can support wide field of view or custom optical patterns
- Materials used must be low-cost, support electrical and thermal needs
- Coherent COMO package passes stringent AECQ102 Automotive qualification

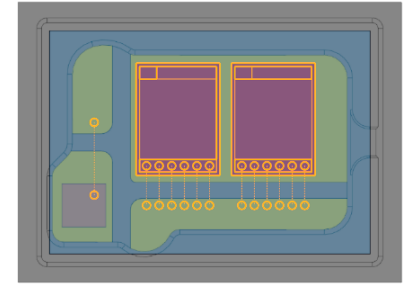
■ Co-packaging VCSEL with driver can improve rise and fall times and reduce EMI

■ MetaOptical Elements (MOEs) increasingly used for space-savings for complex optics

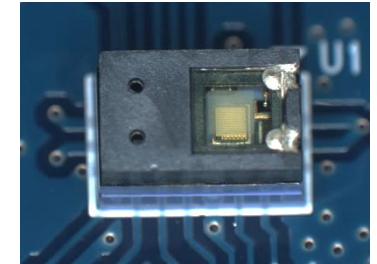
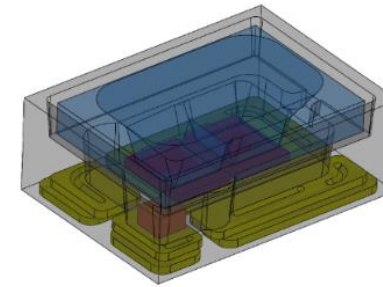
- Subwavelength features defined by lithography at wafer level
- Lenses, diffusers, splitters, multi-function optics
- Flat, smaller than conventional lenses
- High efficiency
- Highly reliable, moisture resistant



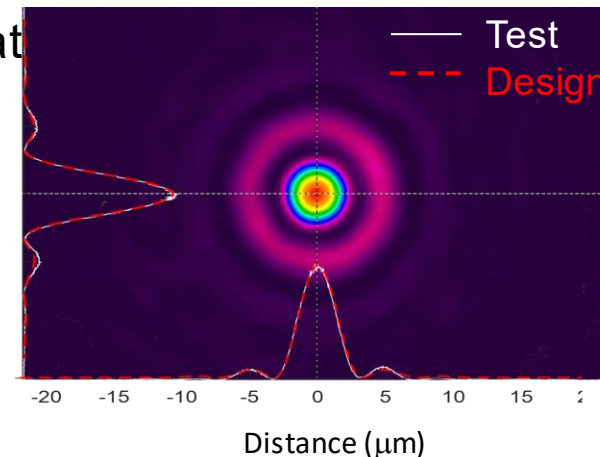
2-in-1: VCSEL + monitor PD



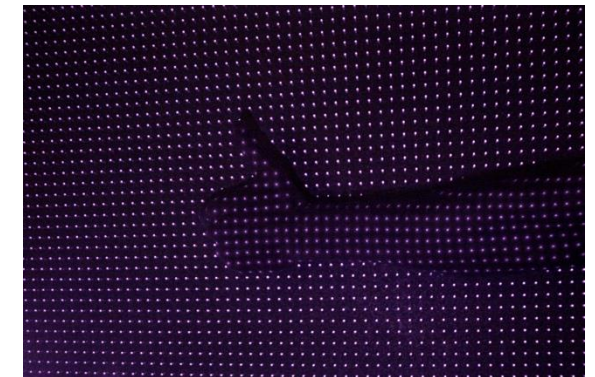
3-in-1: VCSEL, PD, driver



MOE lens: Design vs Actual



Dot projector MOE



BACK SIDE EMITTING VCSEL WITH INTEGRATED COLLIMATED LENS

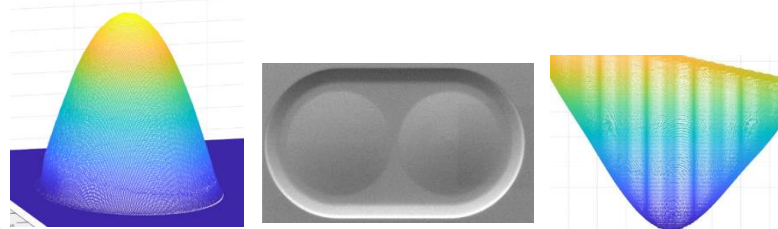
- **Critical in size: small pitch and integrated optics**
- **Low impedance for fast rise/fall time**
- **Platform development**
 - Back Side Emitter
 - 940nm
 - Single mode
 - Integrated collimating lens
 - Grey scale lithography
 - Cu pillar / other connectivity

Features:

- High PCE
- Collimated (simplified optics design)
- Single mode emission possible

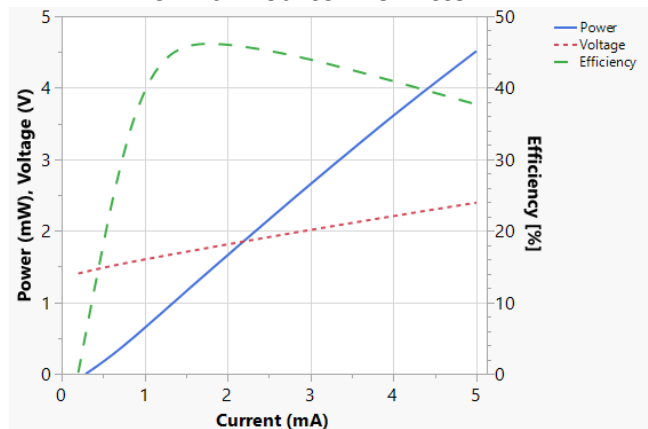
On Chip Lens (OCL)

concave and convex lens demonstrated



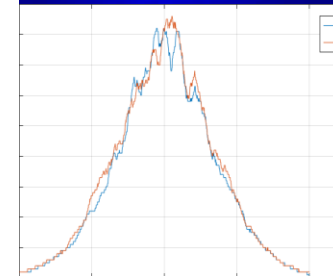
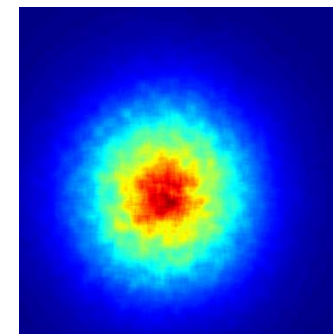
Light – Current – Voltage – PCE

Normalized to 1 emitter

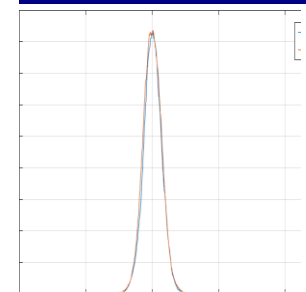
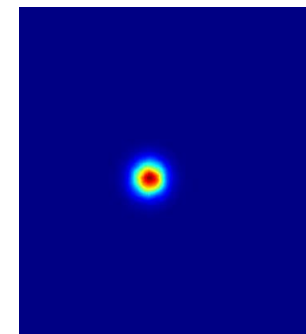


Far field data

No lens



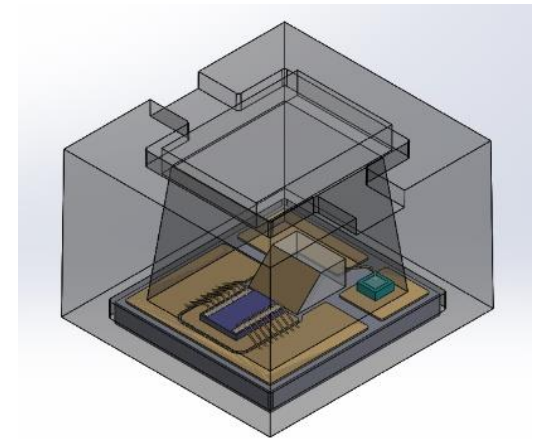
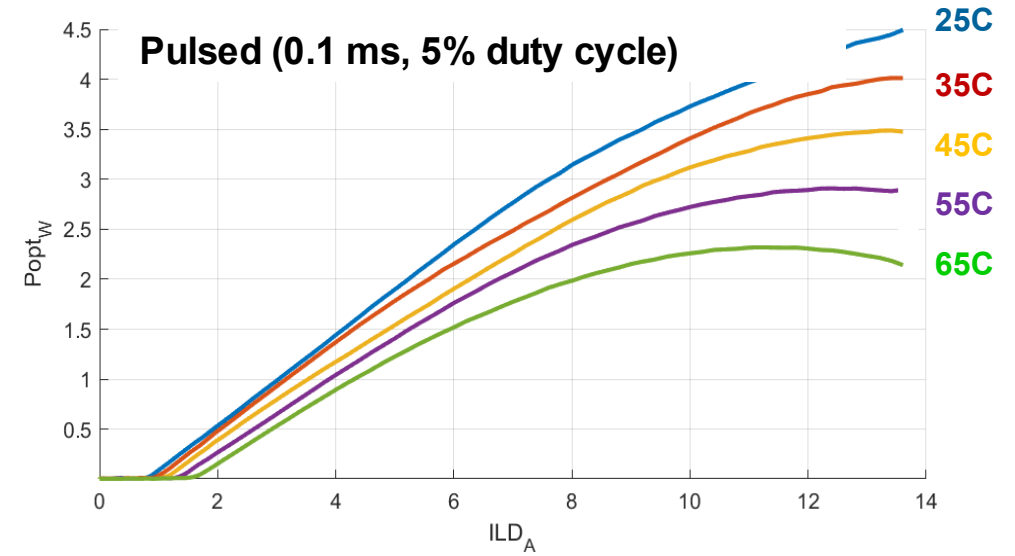
With collimation lens



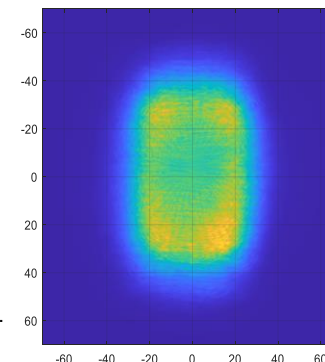
- Divergence without lens is ~18deg.
- With lens, collimation achieved (3°)

SOURCES FOR SWIR SENSING

- **High power InP edge emitting laser (EEL) at 13xx nm**
 - 2-3W at 1380nm at 25°C
 - Array of single mode emitters
 - Packaged in low-cost consumer packaging with optics
- **Advantages**
 - Differentiation not seen in visible or IR/nearIR cameras
 - Higher resolution while meeting eye safety - Eye is less responsive at 13xx which allows higher power
- **Renewed efforts on Long Wavelength VCSELs to develop lower-cost SWIR sources**
 - GaInNAs
 - Wafer bonding InP-based onto GaAs substrates
 - Still far off from InP-based EELs



Uniform illumination with diffuser



BIO-SENSING IN CONSUMER ELECTRONICS DEVICES

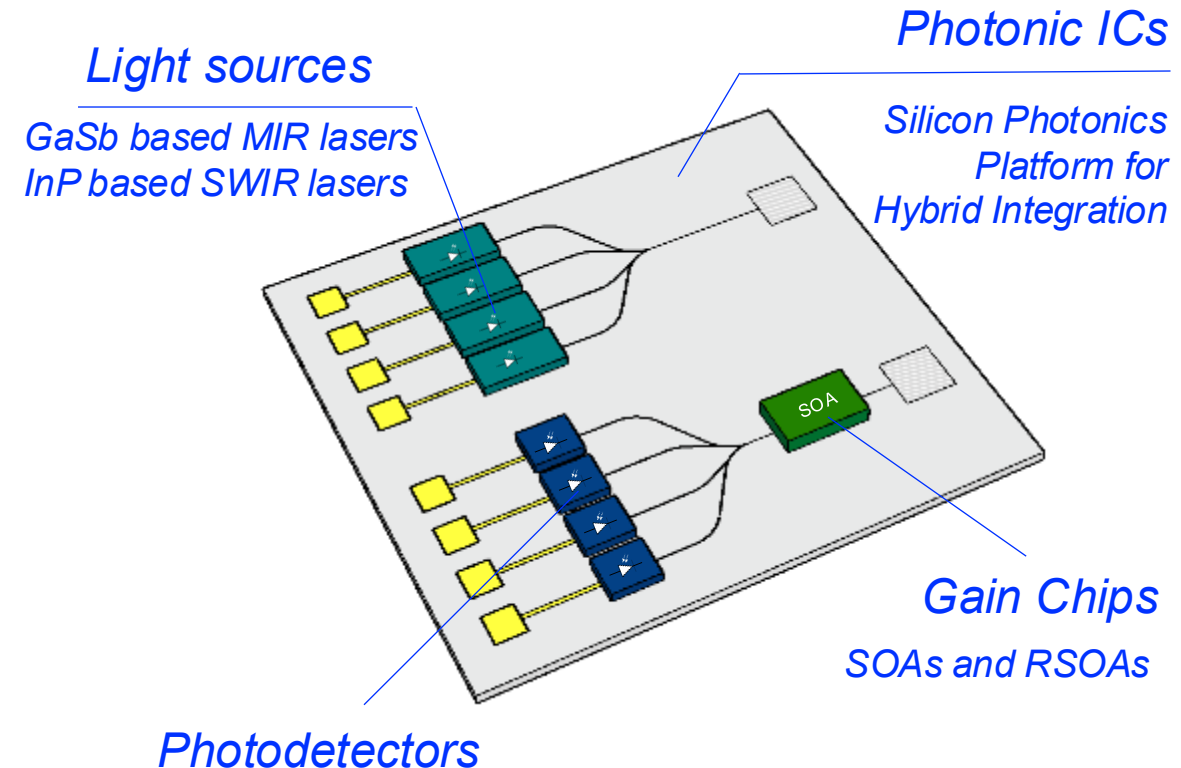
- Growing number of applications for wearable sensors in consumer electronics
- Smart watches and other wearable devices evolving into personal health monitors
- Non-invasive, continuous monitoring
- Trend towards pro-active and preventive medicine, instead of "sick-care". Anomalies in the body are detected before they can develop into an illness.
- Driven by advances in data analysis and machine learning.
- Long-term goal: Shrink an entire lab into a wearable device



Smart Watches



Ear Phones



INTEROPERATION BETWEEN SILICON PHOTONICS-BASED 800G DR8 AND EML-BASED 800G DR8

- Interoperation between modules using different modulator technologies is critical for system operation
- Interoperation between EML-based DR8 and SiPh-based DR8 has been demonstrated over 2 km SSMF
 - Silicon Photonics-based QSFP-DD DR8
 - Highly integrated Silicon Photonics chip
 - Coherent CW laser
 - EML-based OSFP DR8
 - Coherent EML and photodetector
- Modules with both technologies are intended for deployments of the 800G at datacenters enabled by 25T and 50T switches

