ADVANCES IN ELECTRO-OPTICAL COMPONENTS FOR DATA COMMUNICATIONS

6/21/2024

Anna Tatarczak
Member of Technical Staff
at the CTO Office

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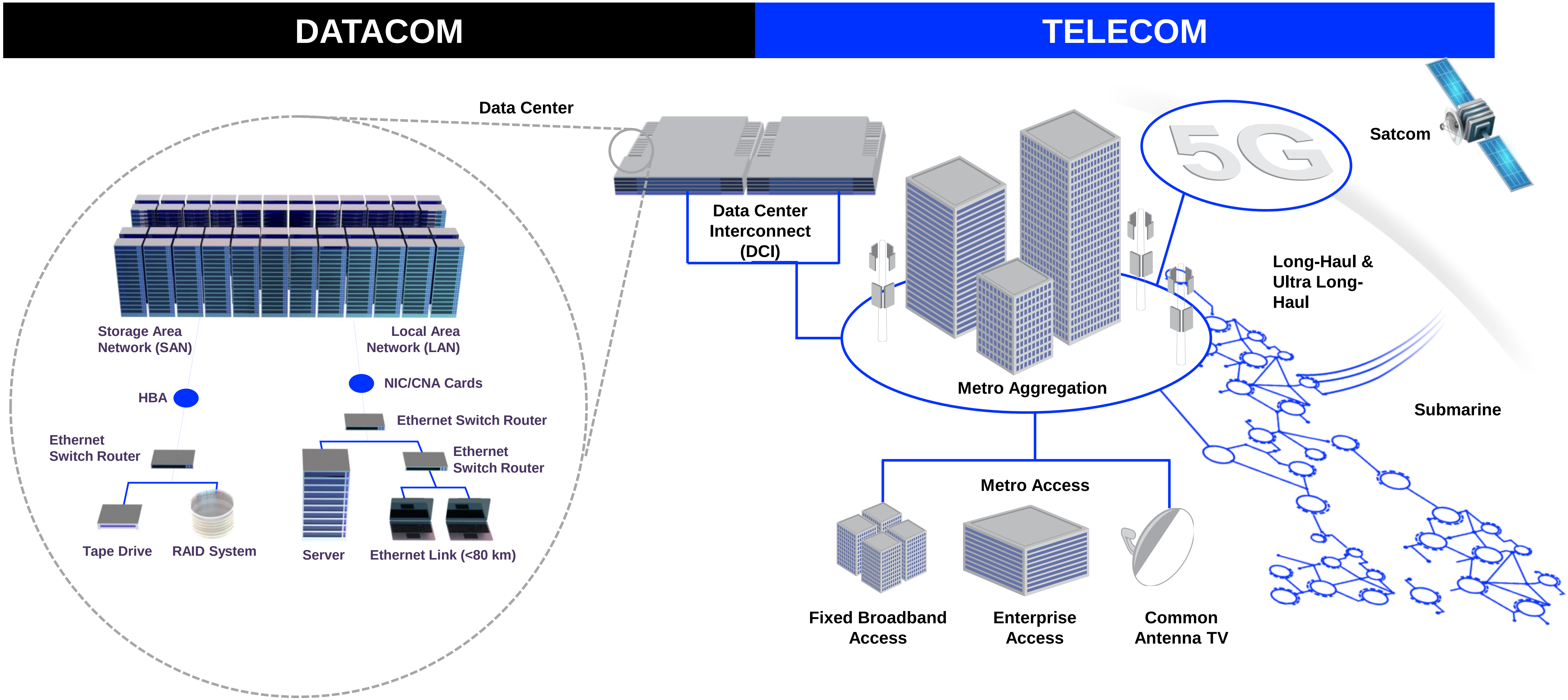
AGENDA

- **Definitions**
- **Standardization driven requirements**
- **Overview of Recent Advances in Electro-Optical Devices**
  - Lasers
  - Modulators
  - Detectors
- **New Developments in Pluggable Modules**
  - Linear and Co-packaged Optics
- **Benefits and challenges of PICs for optical communications**

OPTICAL COMPONENTS FOR DATA AND TELE COMMUNICATIONS

DATACOM AND TELECOM DEFINITIONS



GROWTH DRIVERS FOR ELECTRO-OPTICAL COMPONENTS

DATACOM	TELECOM

- 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

- 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

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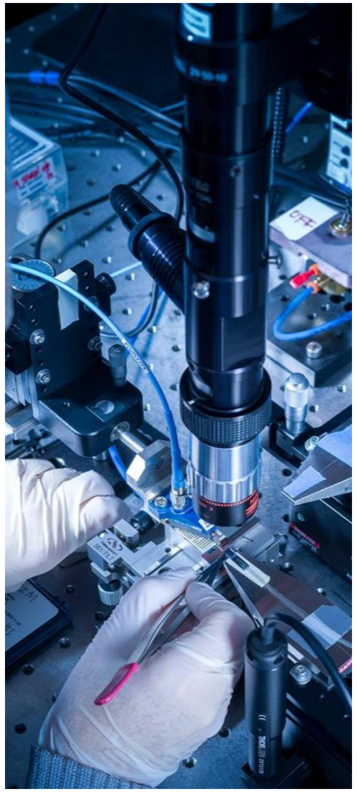
LASER TECHNOLOGIES FOR DATACOM AND TELECOM

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 Indium Phosphide, Silicon Photonics ▪ EML ▪ CW Laser with Silicon Photonics modulator ▪ DFB-MZ	Coherent optics, multiple modulation formats (QPSK, QAM) Indium Phosphide, Silicon Photonics ▪ Narrow linewidth laser ▪ IQ modulators ▪ Coherent mixer and photodiode array



Datacom transceiver R&D in Fremont, CA

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

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OPTICAL COMPONENTS

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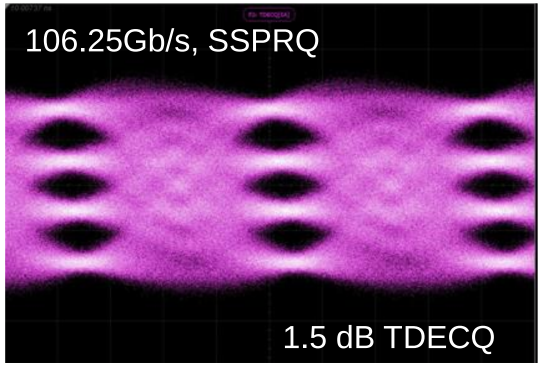
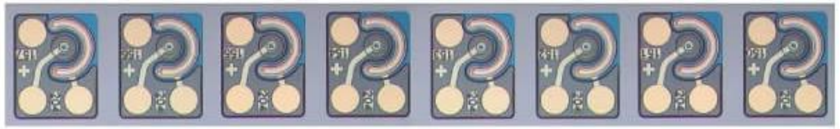
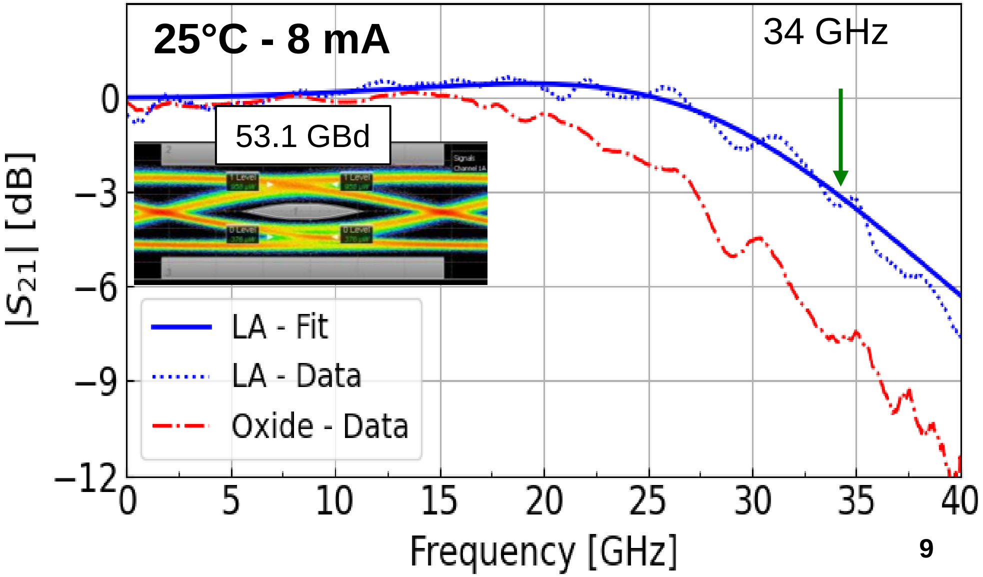
TRENDS IN GaAs VCSELS FOR COMMUNICATIONS

- **GaAs VCSELs**
  - Still the lowest cost, lowest power solution for short reaches up to 50/100m
- **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**
  - >34GHz bandwidth lithographically defined aperture VCSEL was presented at OFC 2024
  - Lithographic Aperture VCSELs Have the Potential to Achieve the Long Lifetimes Required by Datacom Applications and well controlled small apertures
  - 200G PAM4 requires >40GHz bandwidth, which has not been demonstrated with a conventional VCSEL design, but can be supported by lithographically defined VCSEL





VCSEL Technologies Compared
4 µm apertures



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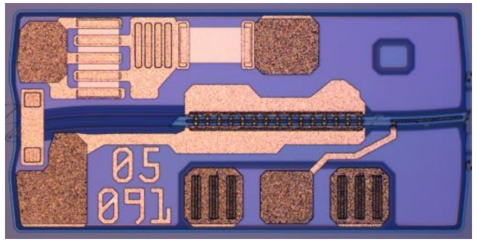
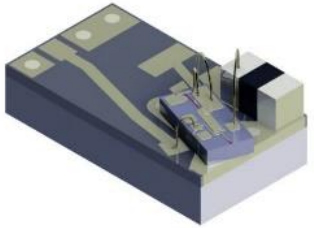
EMLs: 100 GB/S AND 200 Gb/s TRANSMISSION

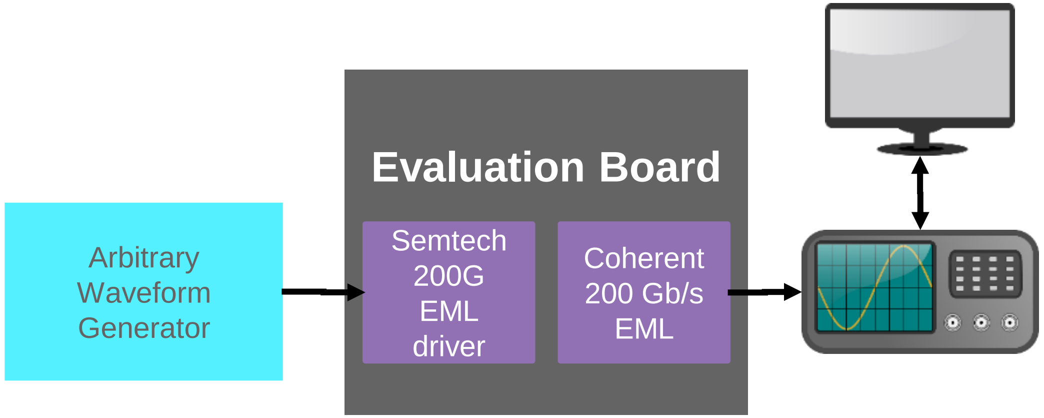
- **InP Electro-Absorption Modulated Lasers (EMLs) are used for 100G/lane today**
  - High EO BW
  - Compact size
  - InP has better electro-optic performance than SiP
  - Mature platform
- **Demonstration of 200G/lane**
  - Monolithically integrated O-band DFB laser and an electro-absorption modulator
  - Supporting 112 GBd PAM4 modulation
  - Optical power 7 dBm, ER 5 dB, low noise 147 dB/Hz
  - Compatible with cost-effective non-hermetic packaging
  - Integrated on-chip RF termination for improved signal integrity

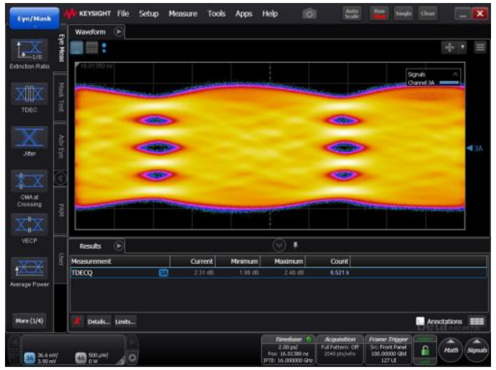


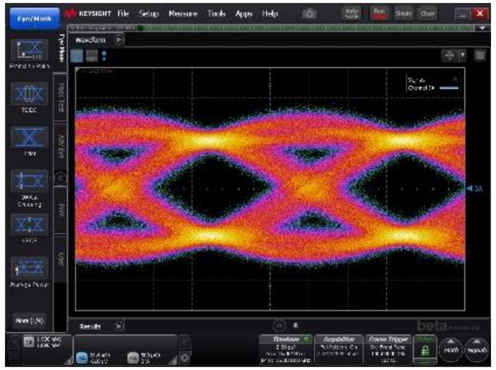
Coherent EML



Coherent EML on CoC







200G PAM4 Optical Eye 100G NRZ

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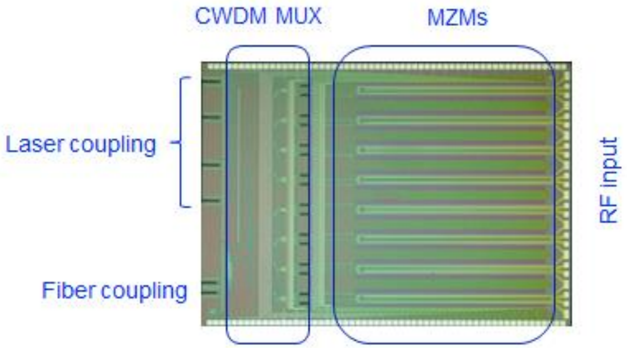
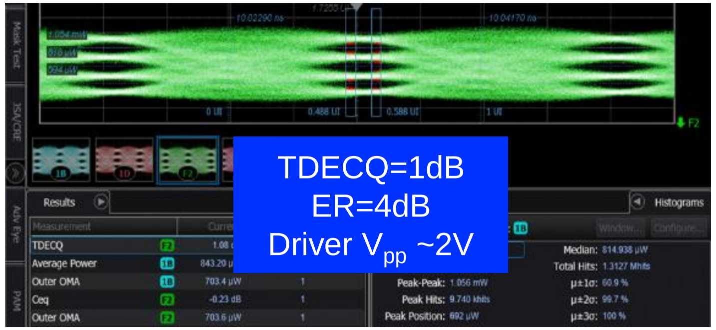
SILICON PHOTONICS FOR 100G/LANE AND 200G/LANE

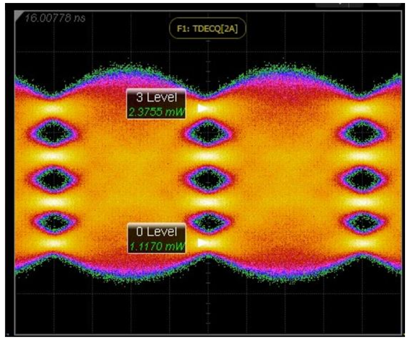
- **Silicon Photonics**
  - Silicon photonics can reduce module cost and complexity by fewer lasers and integration of passives
  - New platform
  - Architecture for each module determined based on detailed specs for application
- **>50GHz Silicon Mach Zehnder Modulators and Ge-based photodiodes demonstrated**
  - 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

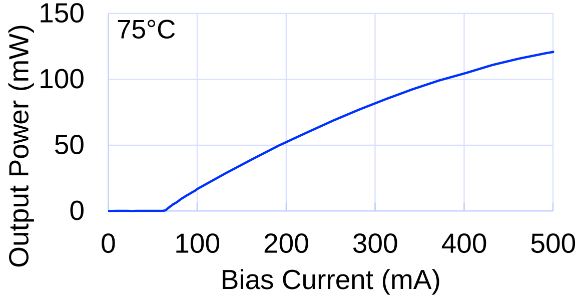


Modulation diagram from 800G 2xFR4 transmitter



224 Gb/s PAM4 optical eye

100 mW Laser



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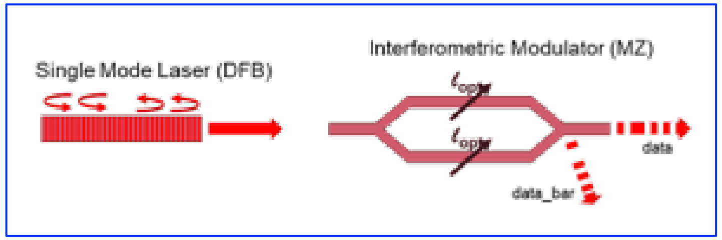
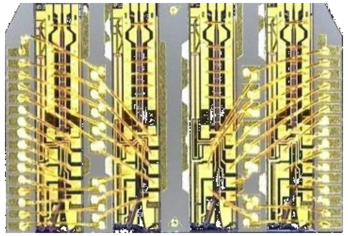
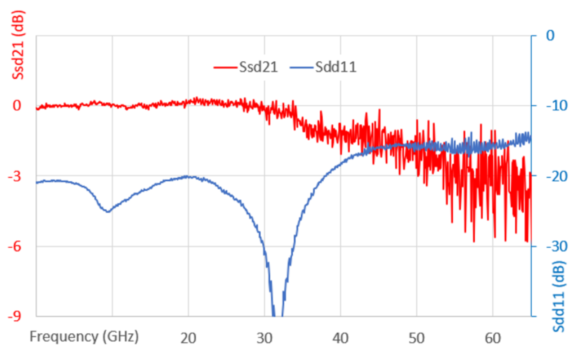
200Gb/s DFB-MZ
A HIGH PERFORMANCE ALTERNATIVE TO EML

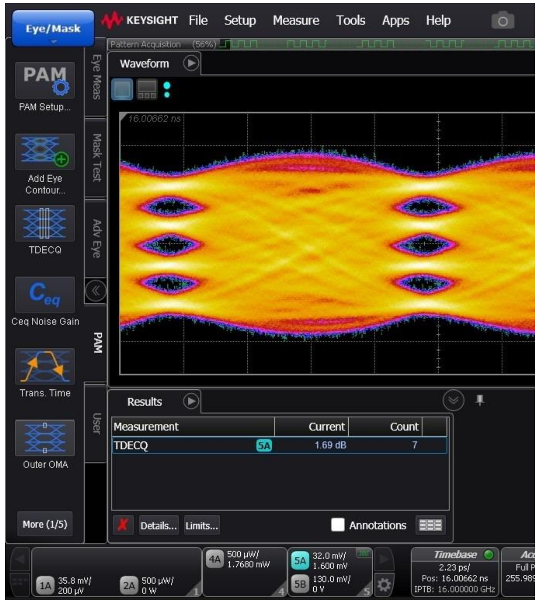




Coherent DMZ CoC, 4ch

- **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

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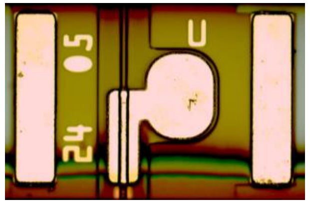
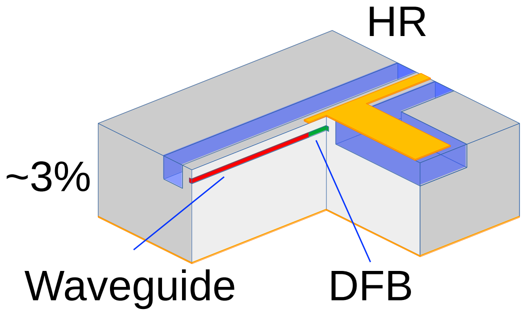
HOW FAR CAN WE PUSH DIRECTLY-MODULATED INP LASERS?

100Gb/s PAM4 laser

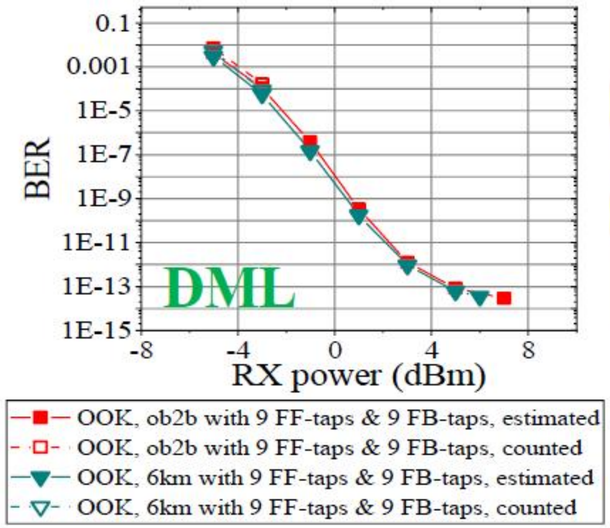


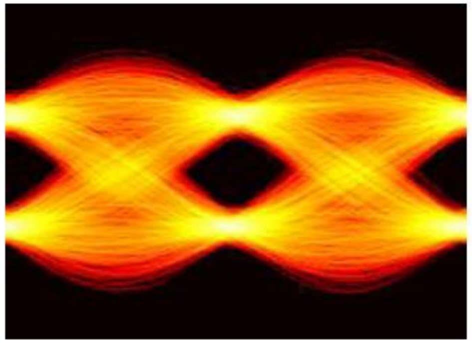
DFB+R Laser



- **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)

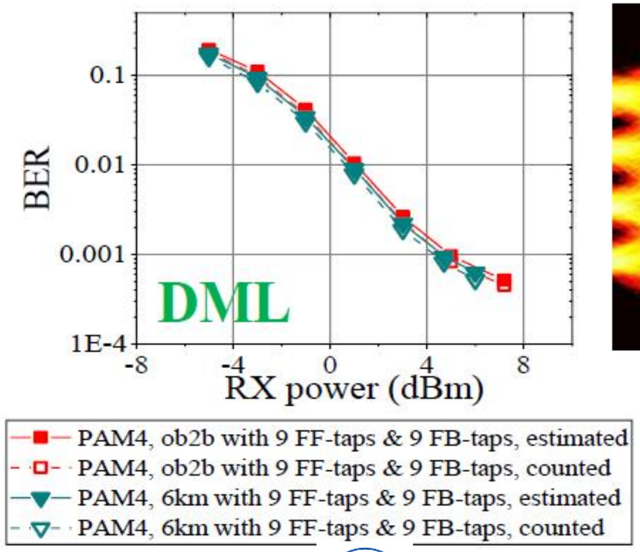
106.25 Gbaud OOK, 6km

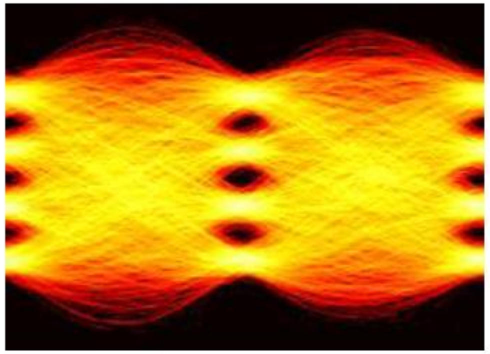




106.25 Gbaud OOK with DML, 6km

106.25 Gbaud PAM4, 6km

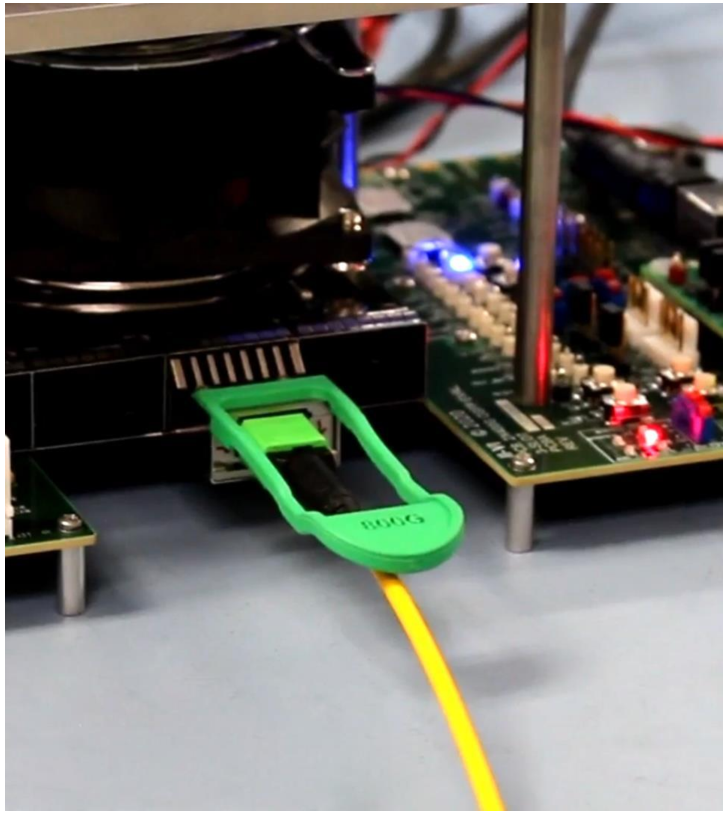




106.25 Gbaud PAM4 with DML, 6km

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 SMF**
  - 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



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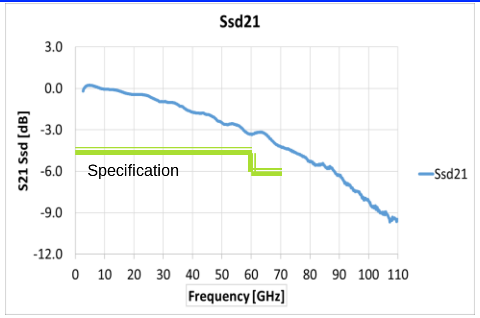
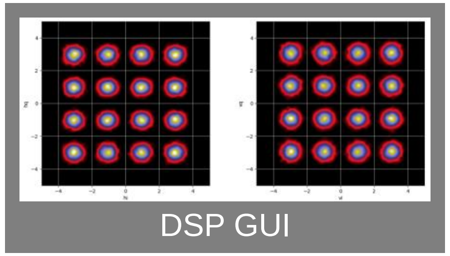
InP PHOTONIC INTEGRATED CIRCUITS (PICs) FOR COHERENT OPTICS TRANSCEIVERS

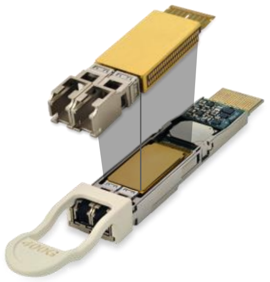
- **InP PIC has best electro-optic performance, good fit for coherent transceivers**
  - Especially for high optical output power, long reach such as 400G and 800G Metro and Long-Haul
- **Integrated InP PICs demonstrated:**
  - Wavelength-tunable narrow-linewidth laser, semiconductor optical amplifiers, IQ modulators, coherent mixer, photodiode array.
- **Advantages of InP**
  - Bandwidth to support >128 Gbaud modulation
  - Low insertion loss and low drive voltage yield 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

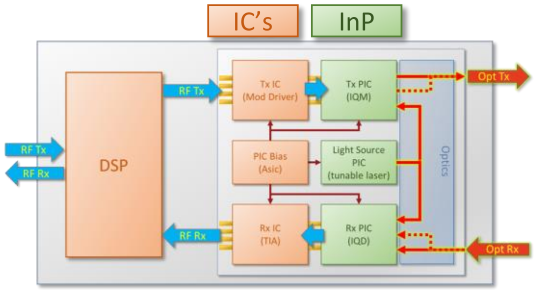
Demo of **800G** coherent transmission
with **140 Gbaud IC-TROSA**





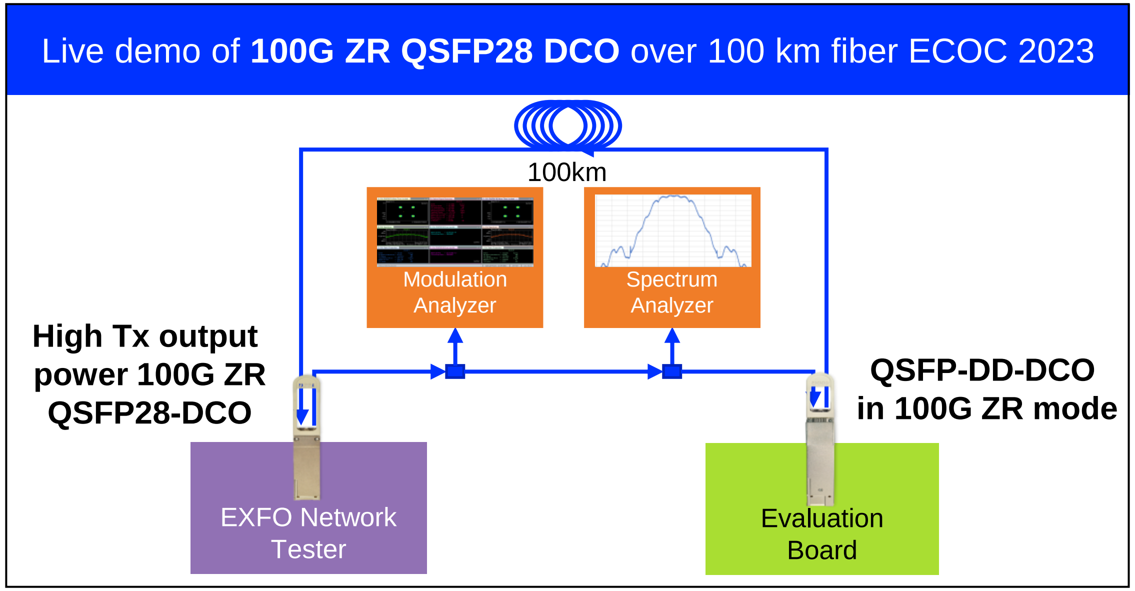
Demo of **400G QSFP-DD DCO**
over 75 km and 430 km (with amplifiers)



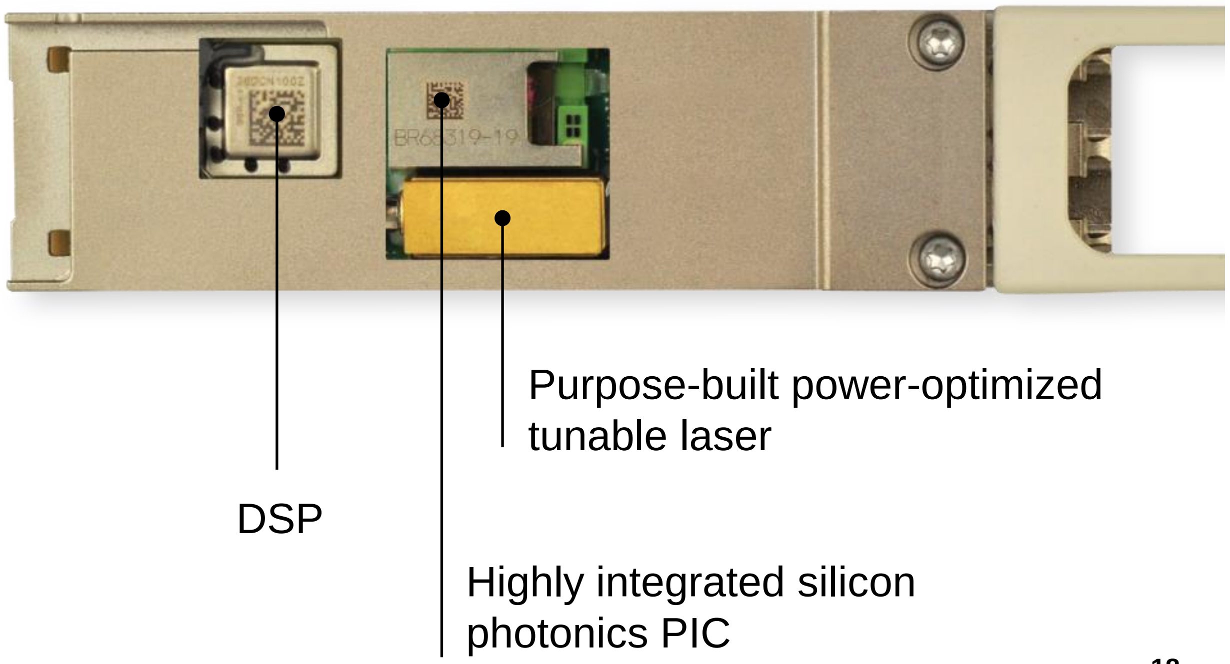


SILICON PHOTONICS FOR COHERENT OPTICS TRANSCEIVERS

- 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



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BEYOND 200GBSP
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

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HIGHER BANDWIDTHS MODULATOR TECHNOLOGIES

- **Multiple materials support high bandwidth EO modulators**
- **Other important parameters to consider**
  - Loss, form factor and efficiency (Vπ*L), energy consumption, reliability, compatibility with silicon/InP fab, maturity

Modulator Material	Modulator Type	Reported BW	Band	Data rate/ Lambda	Voltage	Reference
TFLN	MZM	110 GHz	O	128GBd	Sub-1 Vpp	1
InP	MZM IQ	100 GHz	C	192GBd	1.1Vppd	2
BTO	MZM	110 GHz	C	256GBd	1.9V	3
SOH	MZM	-	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	500GHz	C	256GBd	0.8V	7

[1] St-Arnault, Charles et al. (2024). Net 1.6 Tbps (4×400Gbps/λ) O-Band IM/DD Transmission Over 2 km Using Uncooled DFB Lasers on the LAN-WDM grid and Sub-1V Drive TFLN Modulators. Th4C.6. 10.1364/OFC.2024.Th4C.6.
[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).

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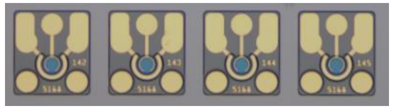
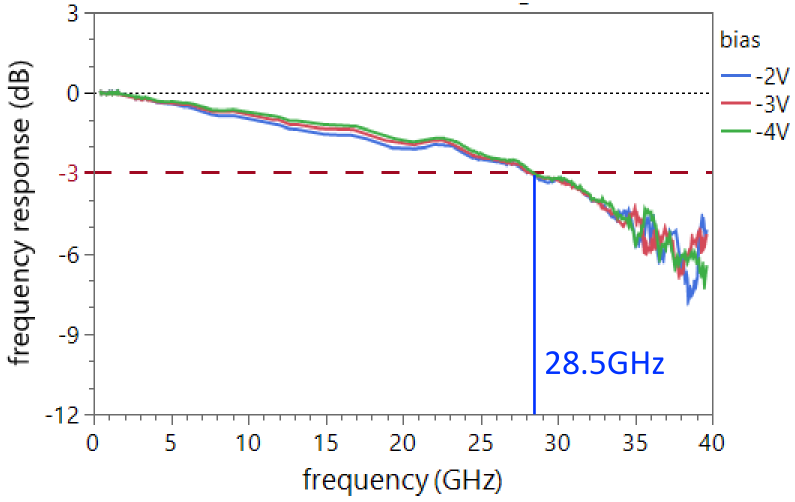
RX

PHOTODIODES FOR 100G/LANE AND 200G/LANE

- **GaAs PDs**
  - >28 GHz bandwidth at -2V with 32µm aperture diameter for 56GBd 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 µm
    - 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



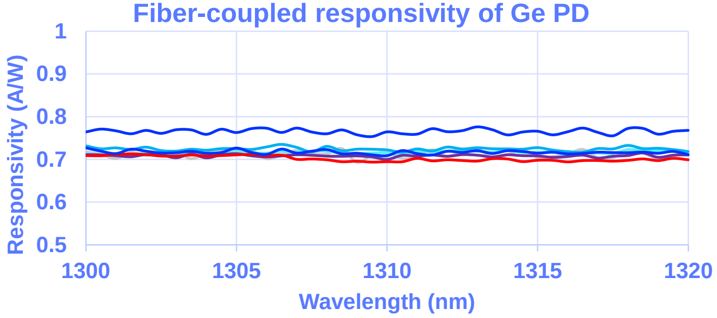
GaAs PDs



InGaAs/InP PDs

4x100G

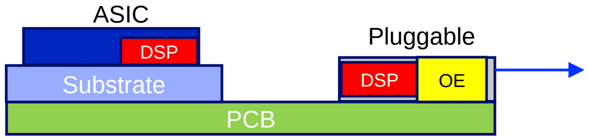
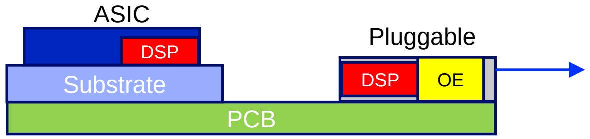
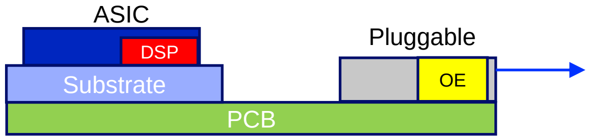
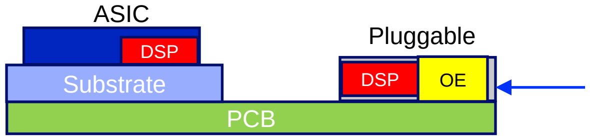
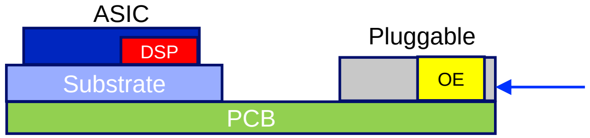
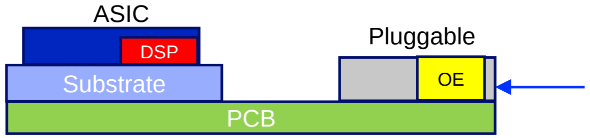
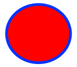
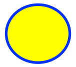
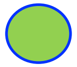
4x200G



CONSIDERED ARCHITECTURES

NEAR TERM TRANSCEIVER CONFIGURATION TRENDS
TRANSMIT RE-TIMED OPTICS (TRO) AND LINEAR PLUGGABLE OPTICS (LPO)

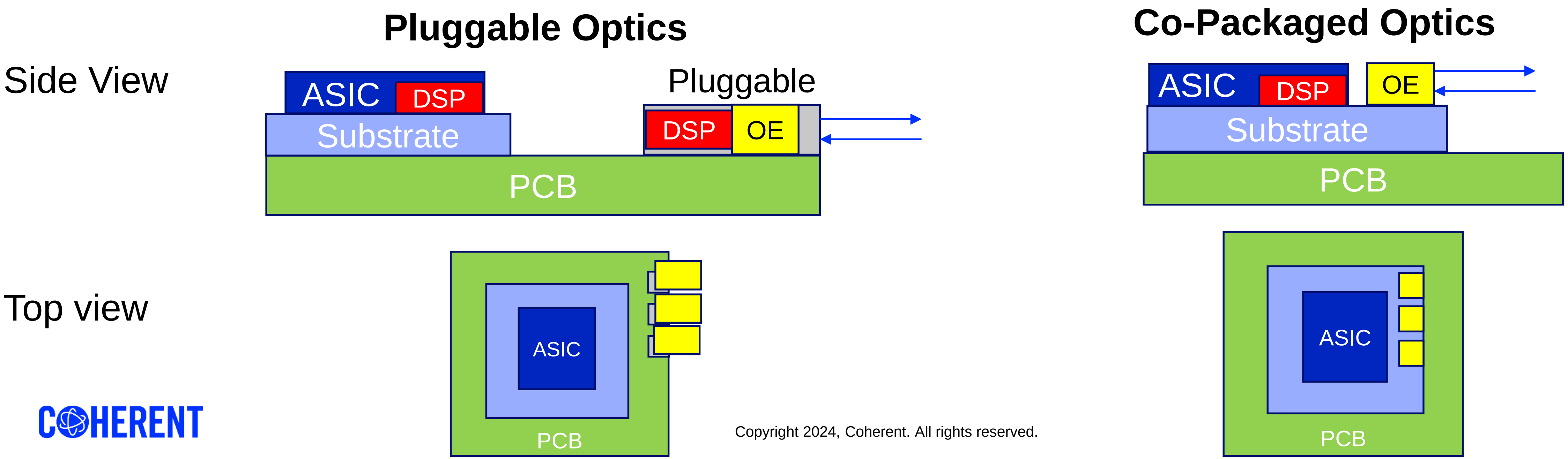
- **New configurations driven by higher energy efficiency requirements**
- **TRO and LPO remove retiming to decrease overall system power consumption, latency, cost**
- **Removing retiming puts high linearity requirements on optics**

	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			

COHERENT

LONG TERM CONFIGURATION TRENDS
CO-PACKAGED OPTICS (CPO)

- **Pluggable module gets replaced by "chiplets" 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

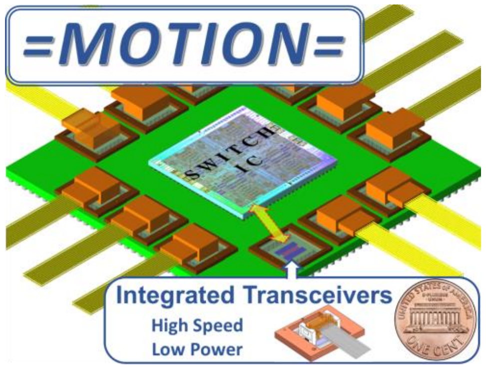


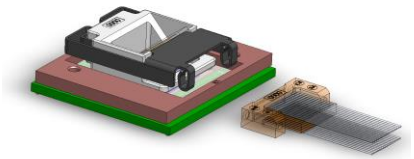
COHERENT

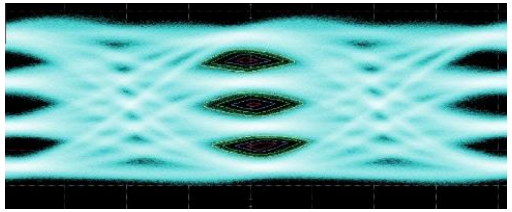
EXTENDIBILITY TO LINEAR, HALF-LINEAR, NEAR AND CO-PACKAGED OPTICS

- **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

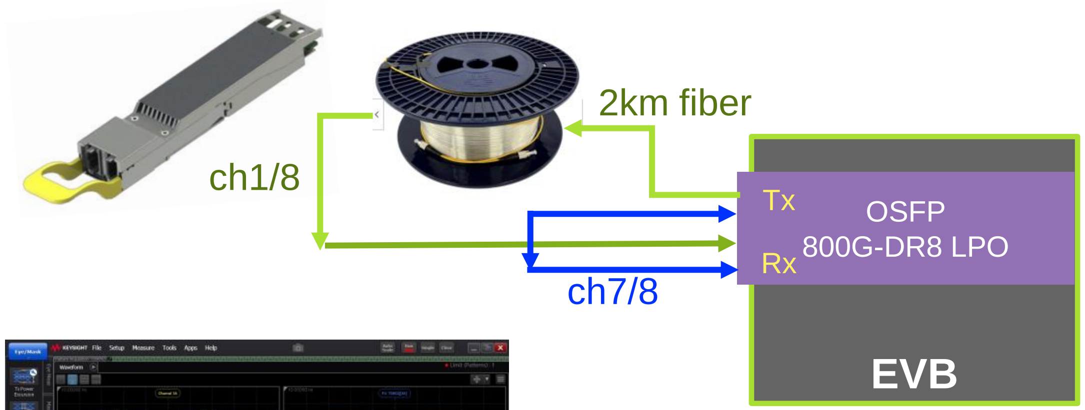


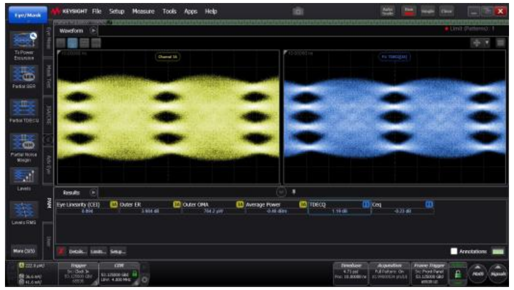




940nm VCSEL @ 112G PAM-4

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





SUMMARY

BENEFITS
PICS FOR COMMUNICATION APPLICATIONS

- **High Bandwidth**
  - Supports high data rates necessary for modern communication systems
- **Compact Size**
  - Integration of multiple optical components into a single chip reduces size and space requirements
- **Energy Efficiency**
  - Lower power consumption compared to discrete optical components
- **High Reliability**
  - Fewer connections and interfaces lead to increased reliability and reduced failure rates
- **Cost Efficiency**
  - Potential for mass production using semiconductor fabrication techniques lowers overall cost
- **Scalability**
  - Easier to scale up for higher performance and capacity by integrating more functions on a single chip.

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CHALLENGES
PICS FOR COMMUNICATION APPLICATIONS

- **Fabrication:**
  - Precision required in manufacturing to maintain performance and yield
  - Need for advanced fabrication facilities and processes
- **Integration:**
  - Combining various optical functions and materials on a single chip
  - Ensuring compatibility and optimal performance of integrated components
- **Manufacturability:**
  - Developing cost-effective manufacturing processes for large-scale production
  - Addressing variability and defects in the manufacturing process
- **Thermal Management:**
  - Managing heat dissipation in densely packed PICs
- **Packaging:**
  - Protecting the delicate components while maintaining performance
  - Ensuring efficient optical and electrical connections

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INNOVATIONS THAT RESONATE