Scalable Coherent Optical Communications

From Trans-Pacific Cables to Intra-Data Center Links

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Overview

- The evolution of coherent optical communications and Ciena’s contributions
- Coherent optics trending towards shorter length scales
- Enabling technologies for coherent optical communications
- Professional development resources and personal experiences

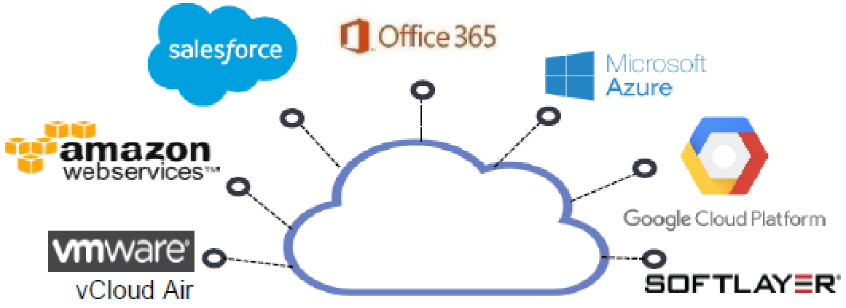
The Evolution of Coherent Optical Communications

Scaling the Internet

Content Providers and Multi-Tenant DCOs experiencing massive traffic growth

70% of mobile traffic will be video by 2021 Facebook, Oct 2016	>10 times Network bandwidth that M2M traffic will need versus user-machine	160Tbps MAREA Subsea cable capacity built by FB and MSFT

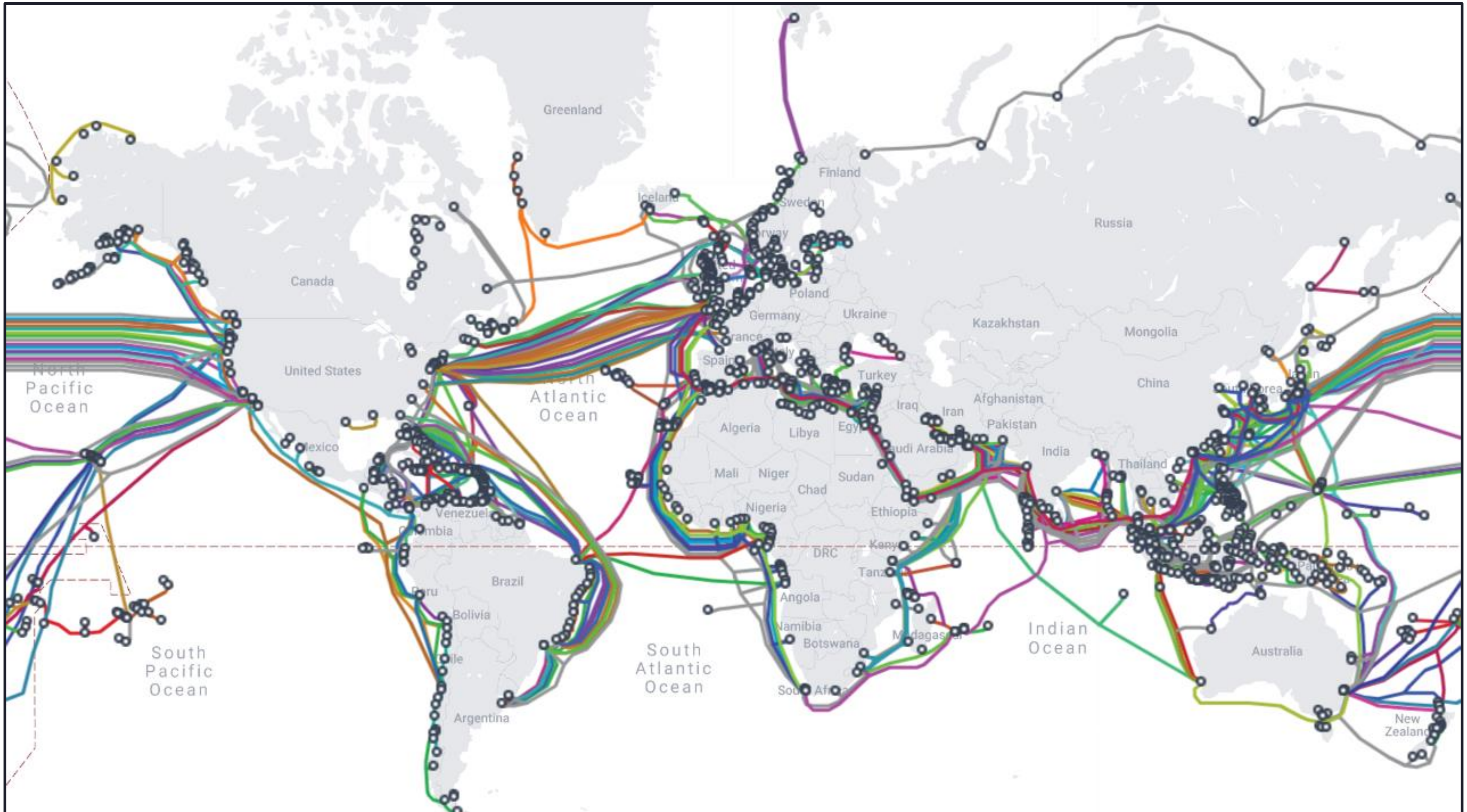
Content providers depend upon simple, scalable, open high capacity platforms that facilitate mass, automated deployments



19.4% CAGR For worldwide spending on public cloud services	5+ Number of cloud providers that Enterprises connect to today	93% of organizations are currently using at least one cloud service

Data Center Operators (DCOs) need greater scale to improve competitiveness for providing interconnect between cloud applications, service providers, and Enterprise customers

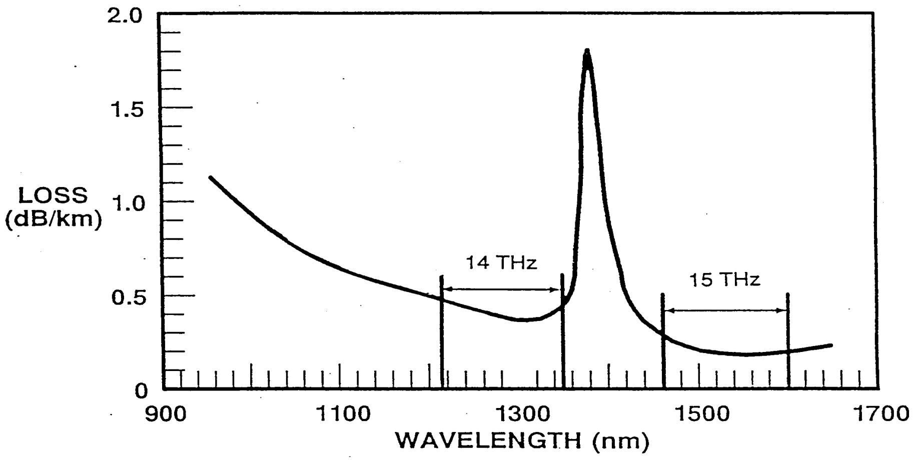
Submarine Cable Map

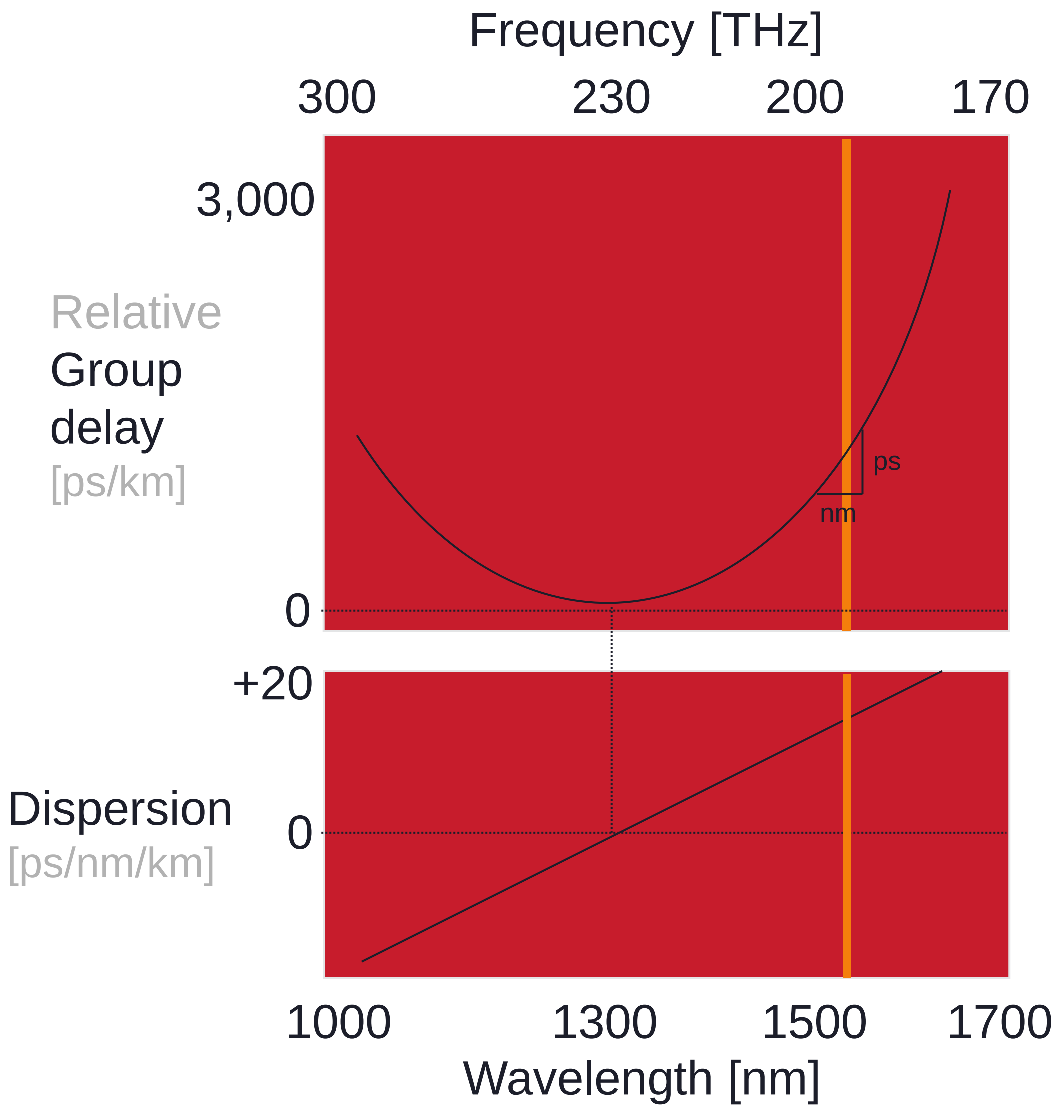


https://www.submarinecablemap.com/

Initial Impairments: Loss and Dispersion

- **Enabling Technologies**
  - Low-loss single mode fiber
  - C+L band technologies
    - Single mode DFB lasers
    - Erbium doped fiber amplifiers
- **Some Benchmarking**
  - 1986: 565 Mb/s across 40 km SMF
  - 2020: 20 Tb/s across 6644 km
    - Marea Trans-Atlantic Cable built by MSFT and FB (8x20 Tb/s = 160 Tb/s)





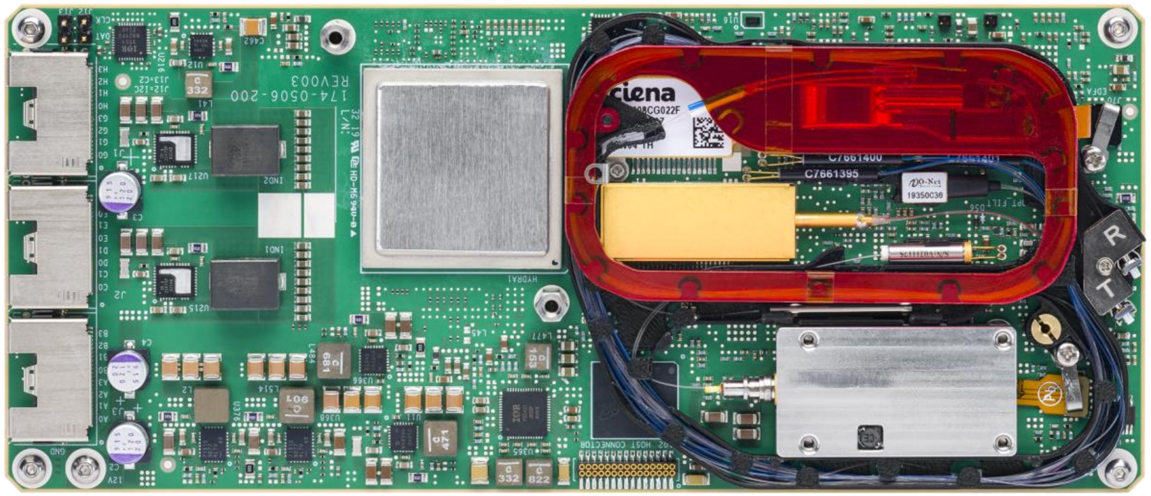
Coherent Modem Applications: Two Categories

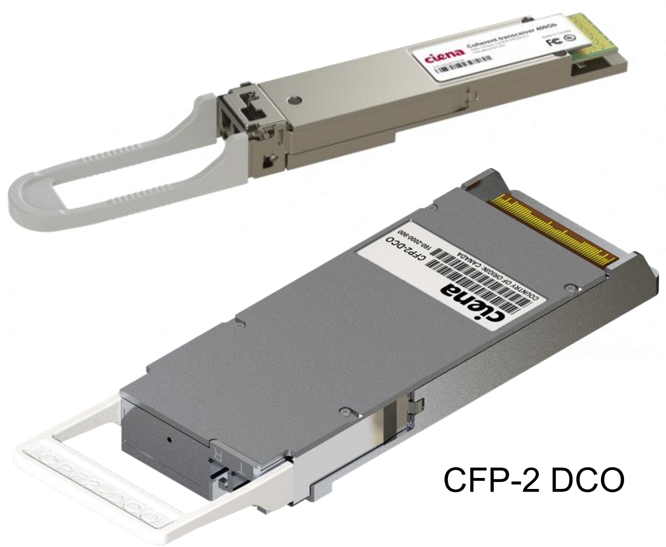
Discrete, board-mounted optics

- WaveLogic3, WaveLogicAi, WaveLogic5e
- Maximum 1-2 modems per faceplate
- Allows larger form-factor, discrete EO components
- Allows functional partitioning
  - e.g. discrete laser, modulator, ICR, etc
- More mature, lower-cost, “off-the-shelf” EO
- Performance, flexibility are key drivers

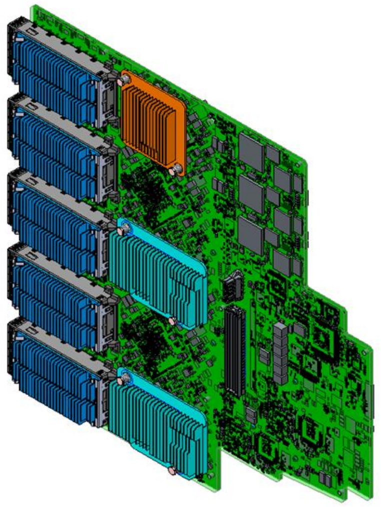
Faceplate-pluggable optics

- WL3n CFP2-ACO; WL5n CFP2-DCO, QSFP-DD
- Higher density: >2 modems per faceplate
- Requires smaller form-factor EO components
- Requires functional integration
  - e.g. SiP COSA
- Less mature, higher-cost EO
- Density, cost are key drivers

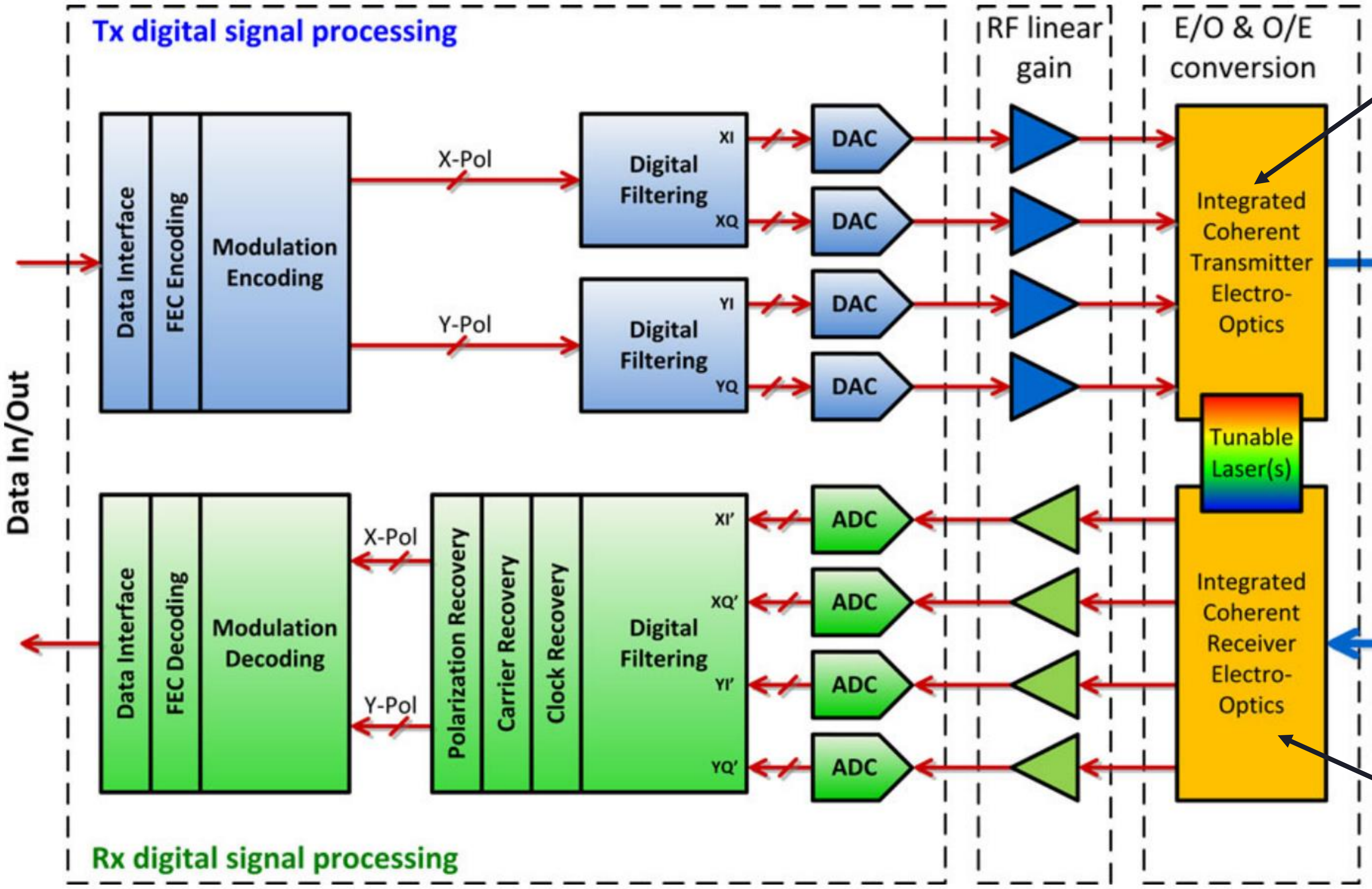


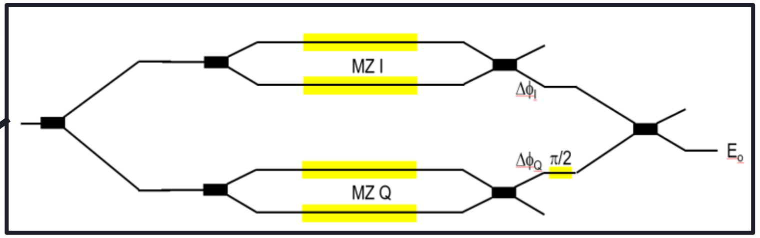


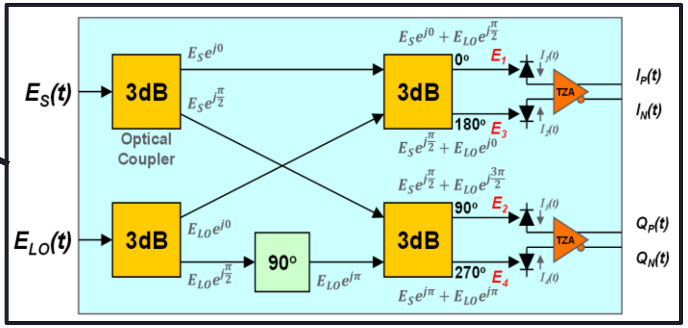
CFP-2 DCO



Coherent Transmitter and Receiver



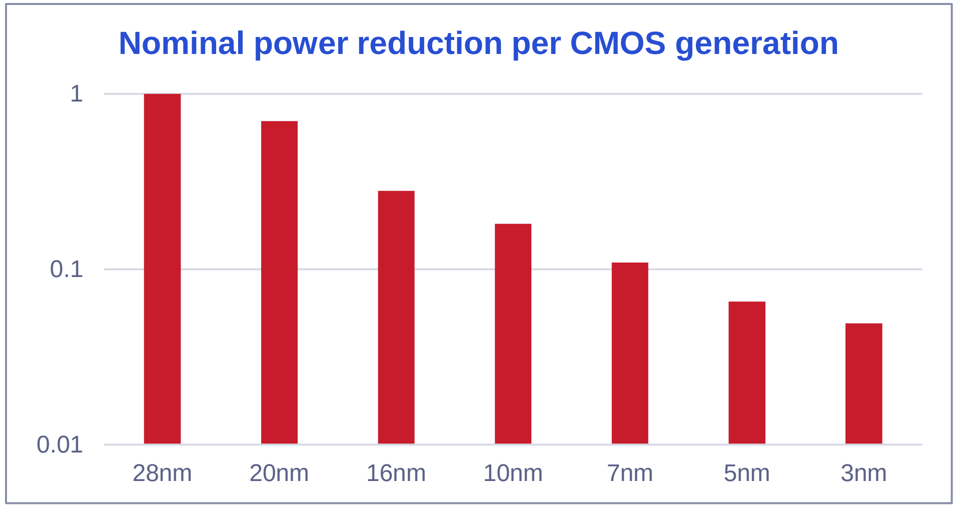


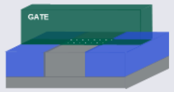
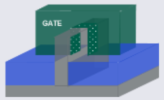
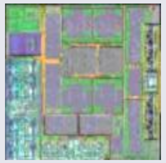
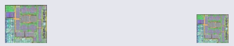


Laperle, C. and O'Sullivan, M., 2014. Advances in high-speed DACs, ADCs, and DSP for optical coherent transceivers. *Journal of lightwave technology*, *32*(4), pp.629-643.

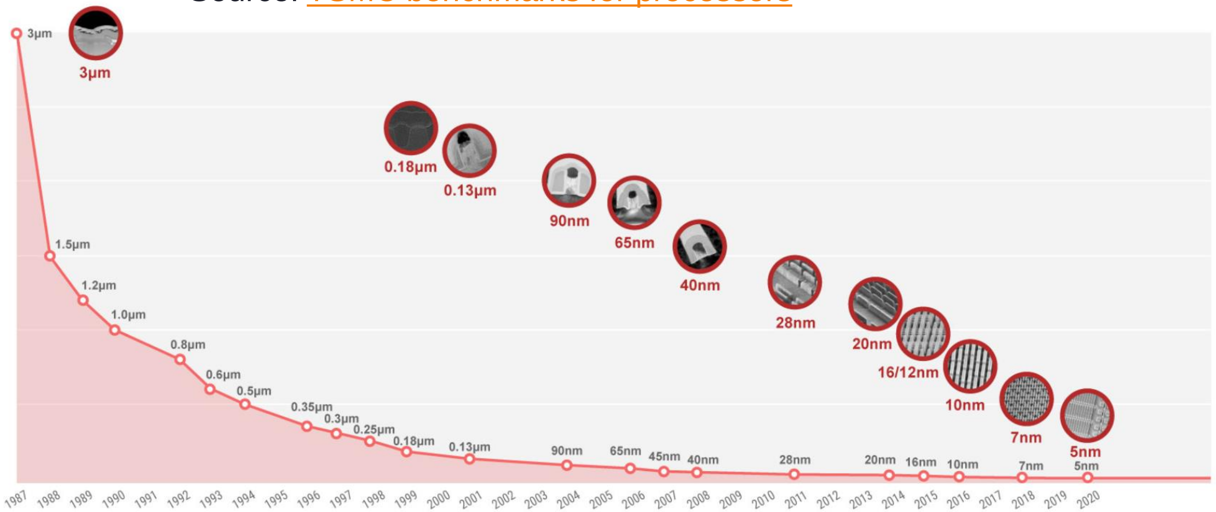
Determining Appropriate CMOS Technology for DSP

Driven by → **1. Power consumption considerations** → **2. Die Area (cost)**



Structure	Planar CMOS technology	finFET CMOS technology	finFET or GAA CMOS technology
Transistor			
Digital gate shrink ratio	 28nm – 1X	 16nm 0.7X; 10nm 0.5X; 7nm 0.35X	 5nm 0.30X; 3nm 0.20X

*Source: TSMC benchmarks for processors



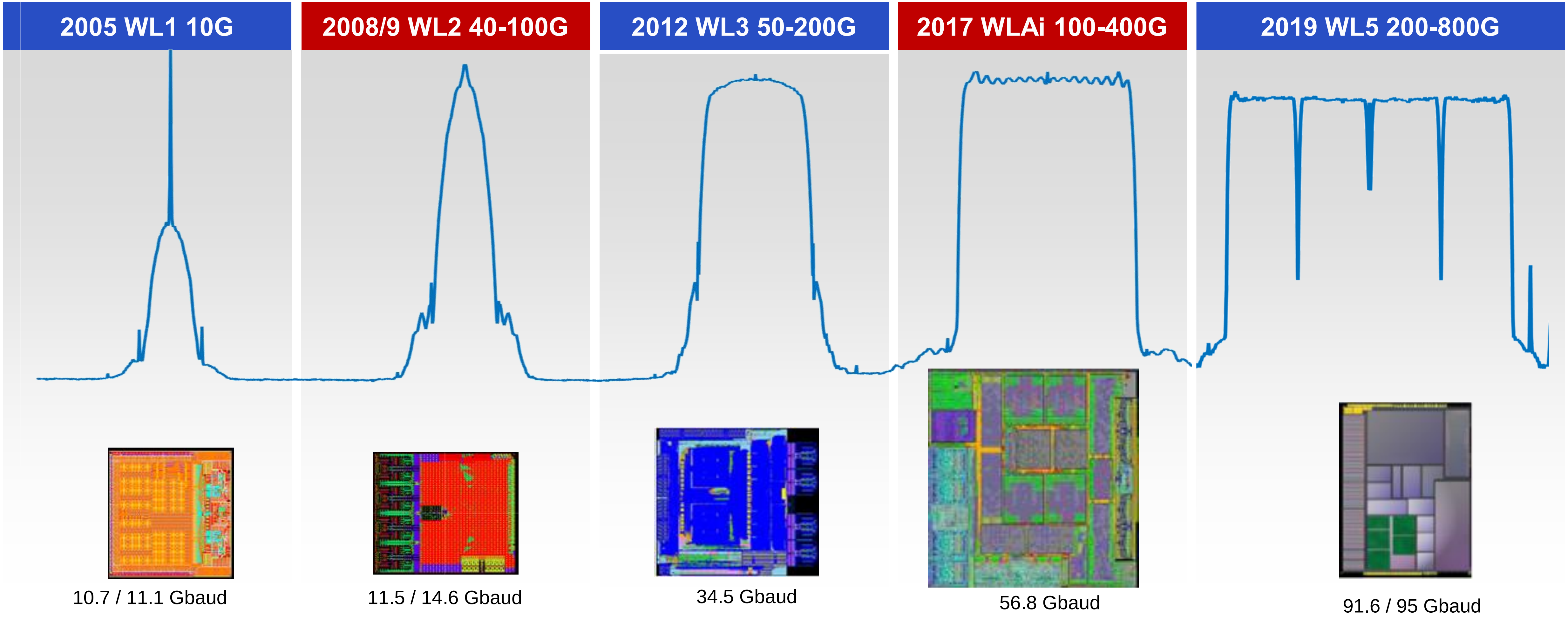
Financial Investment

- 65 & 40/45nm
- 32/28nm
- 22/20nm
- 16/14nm
- 10/7nm
- 5nm
- 3nm

General Time Frame for Wafer Mass Production Start*

Year	2010	2012	2016	2018	2020	2022
Process Node	32/28 nm	22/20 nm	16/14 nm	10/7 nm	5 nm	3 nm

Ciena’s Digital ASICs



We are working on the next generation which will carry more, further.

WaveLogic 3 Nano ASIC

Modulation Formats

- 100G 4ASK for Metro (1000km)
- 100G QPSK for Regional (1800km)

Dispersion Compensation

- Optimized for metro and regional applications

Forward Error Correction

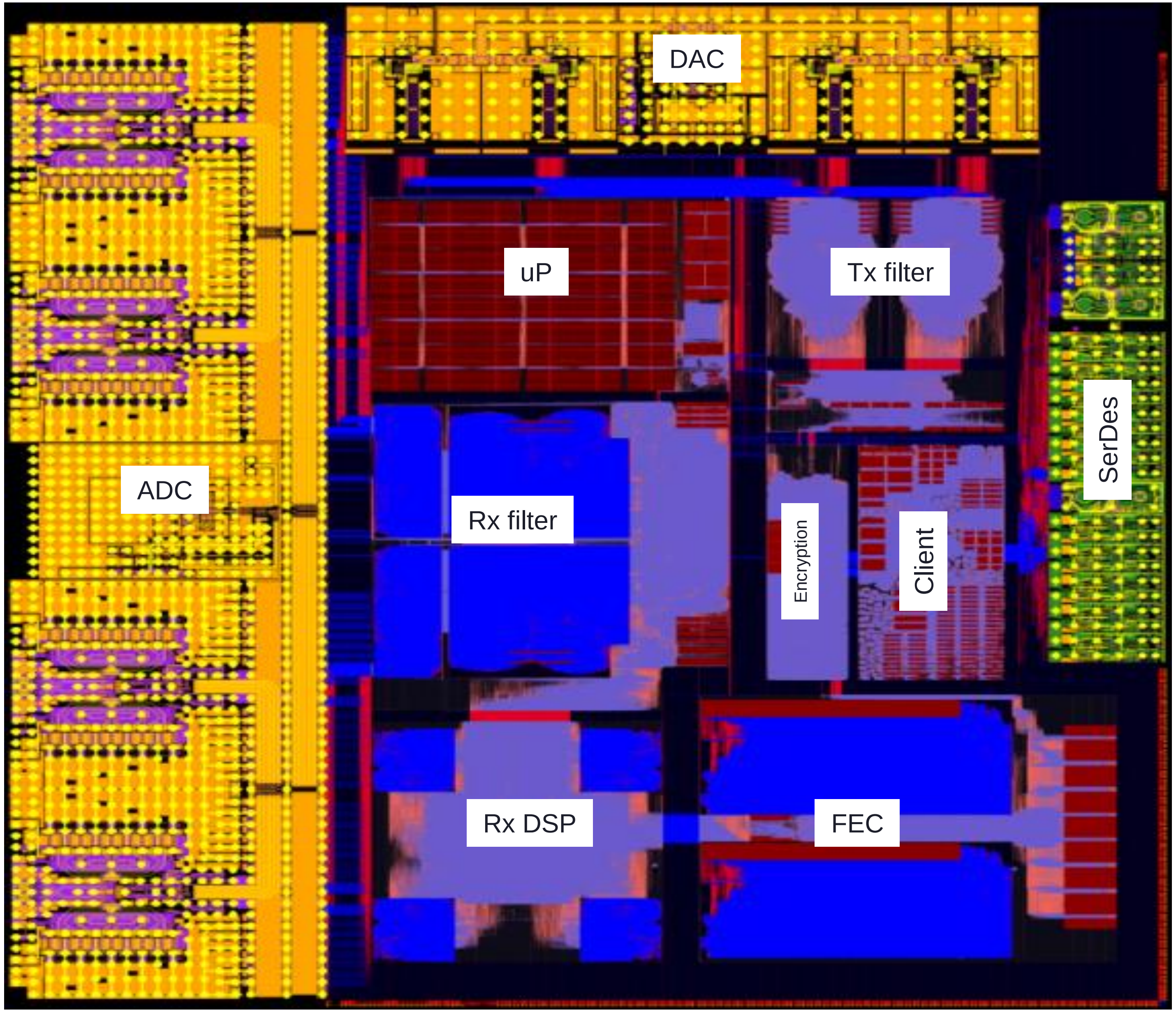
- Ciena's best-in-class soft decision FEC, at lower power
- Reduced power consumption

Client Interfaces

- Configurable 100GbE/OTN client interface
- Enables single slot OTR, MOTR and PKT/OTN XC interface

Encryption

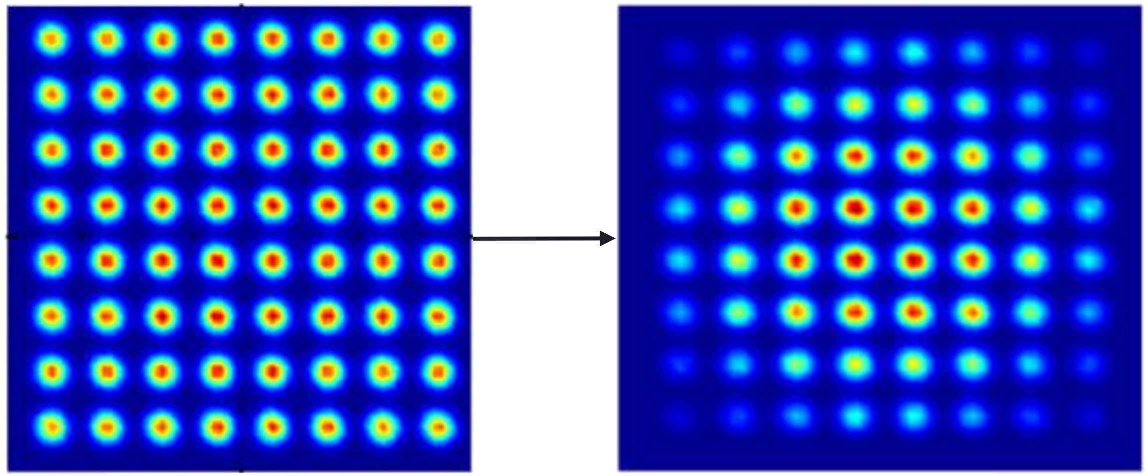
- AES256 line rate encryption

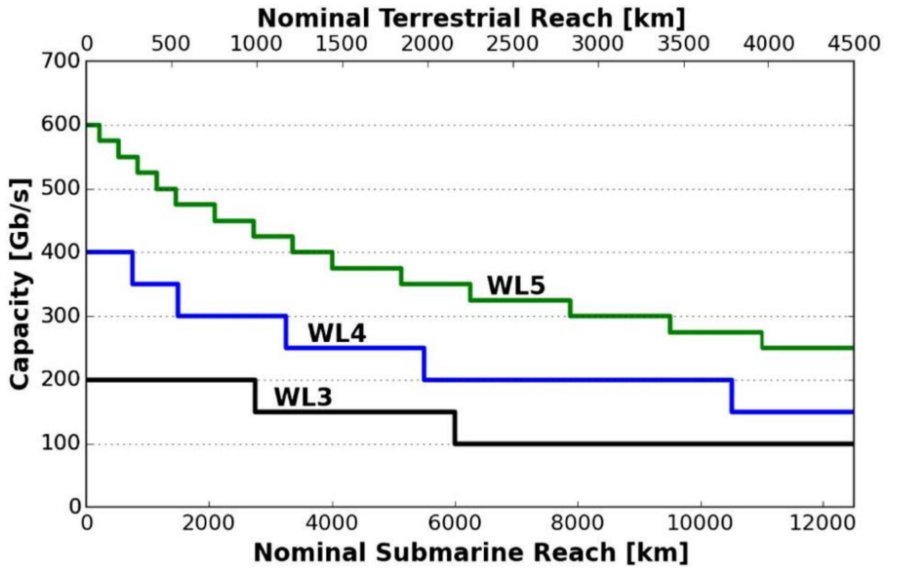


70T ops/s, 32 nm CMOS, 150M gates, 3.7 km of copper

Advanced Transmission Techniques

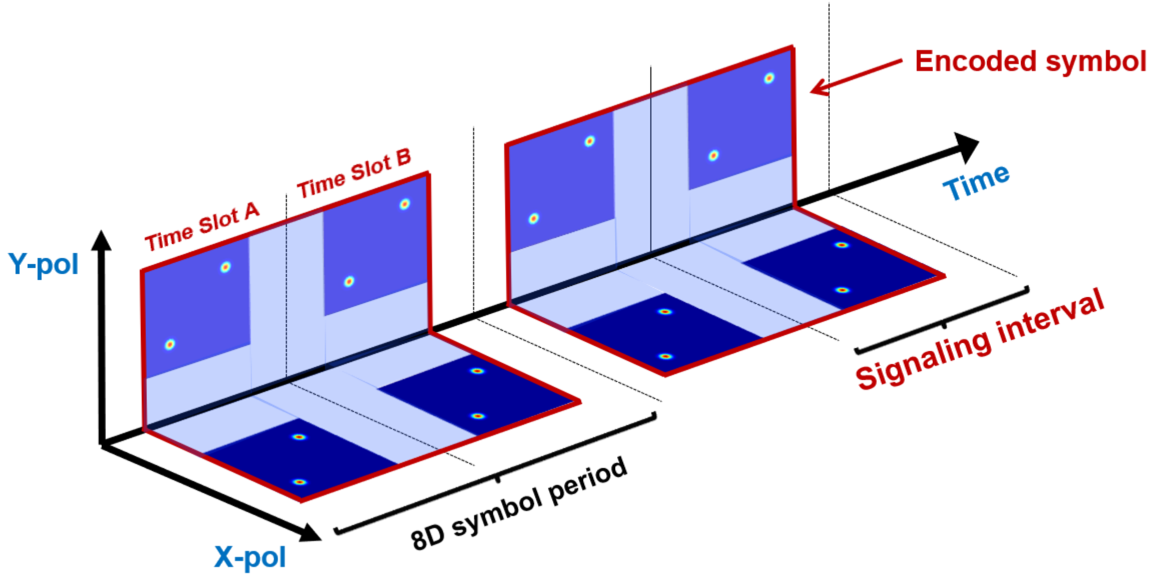
Probabilistic Constellation Shaping

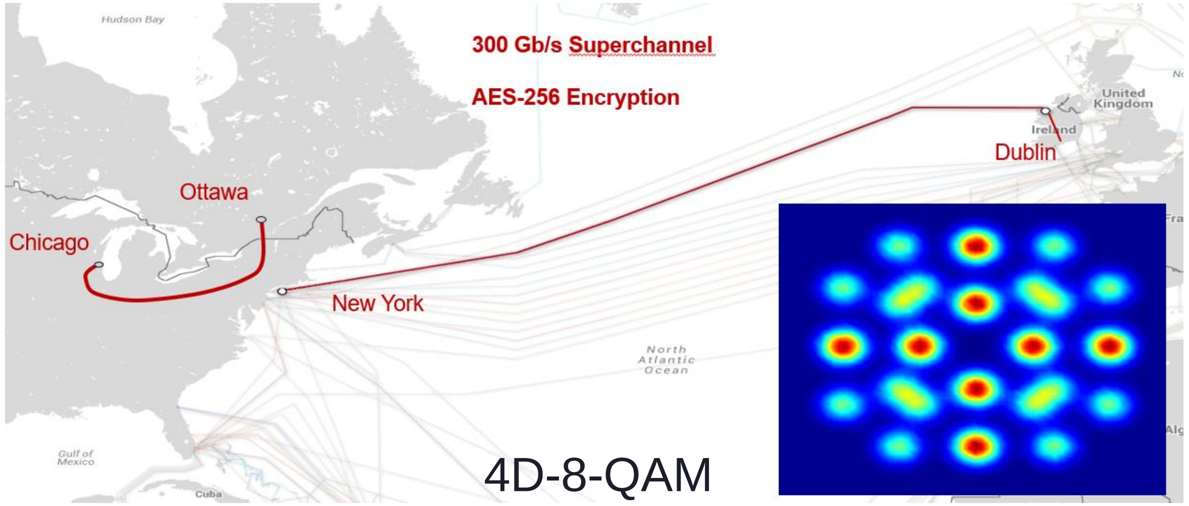




Roberts, K., Zhuge, Q., Monga, I., Gareau, S. and Laperle, C., 2017. Beyond 100 Gb/s: capacity, flexibility, and network optimization. *Journal of Optical Communications and Networking*, *9*(4), pp.C12-C24.

Multi-Dimensional Modulation Formats

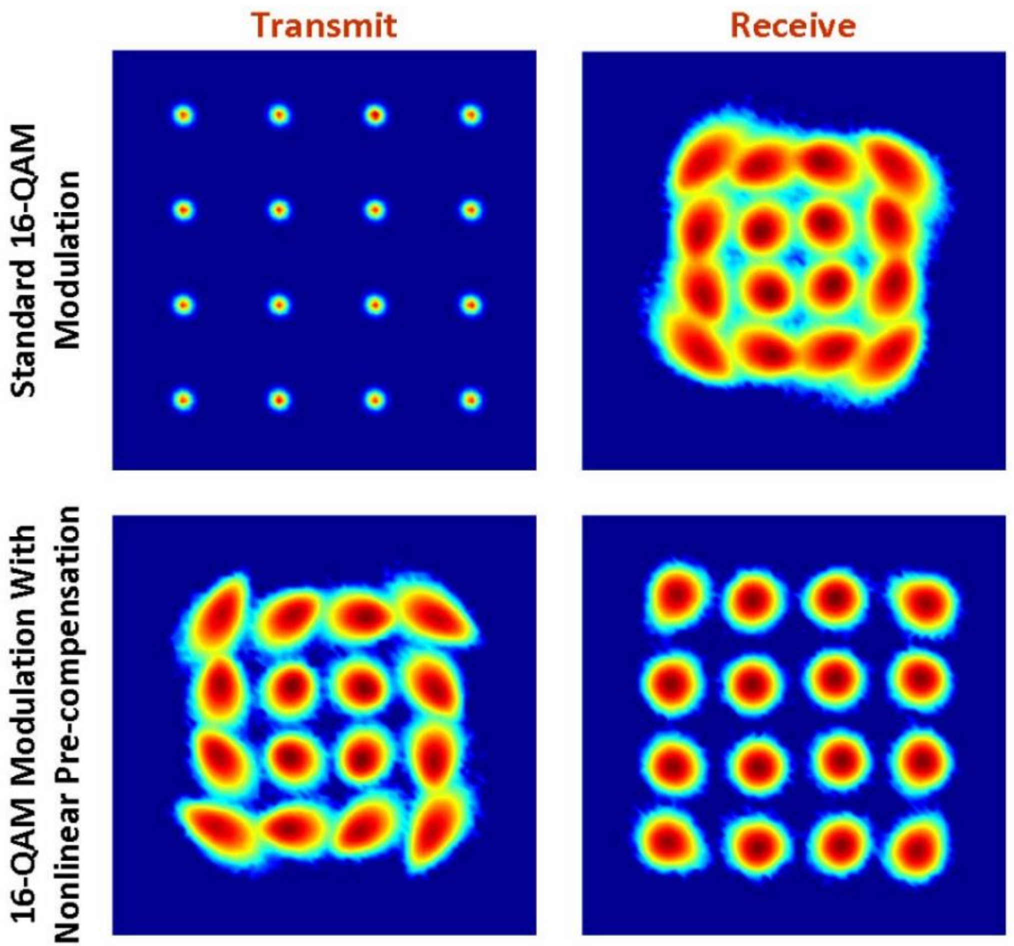




4D-8-QAM

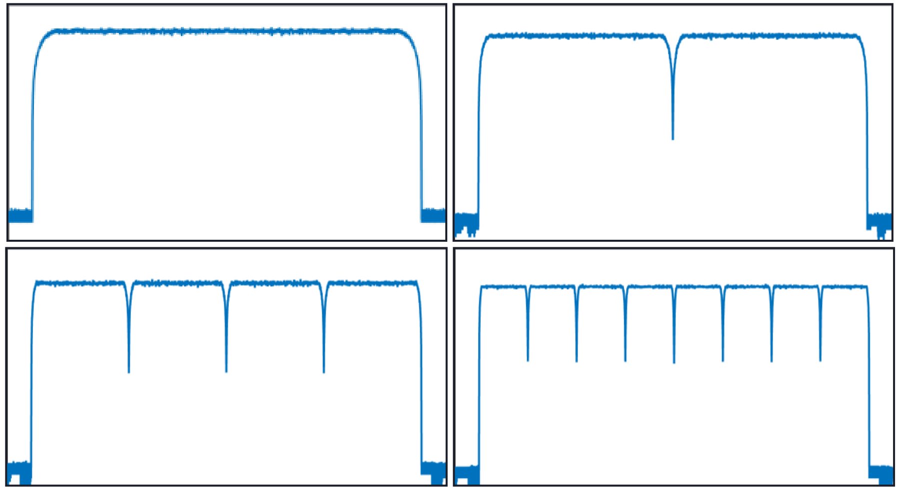
Advanced Transmission Techniques

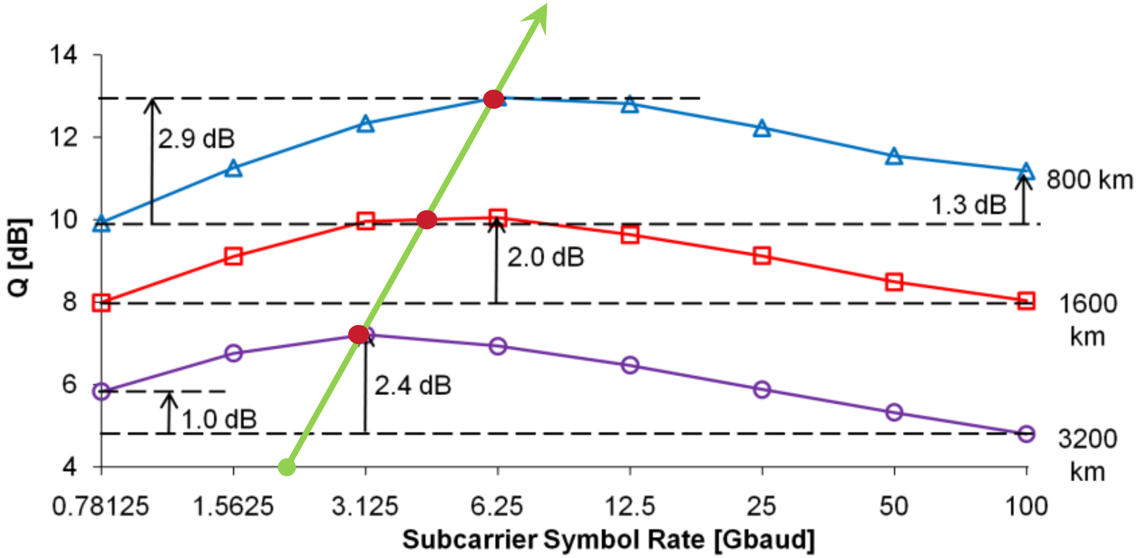
Nonlinear Pre-Compensation



Roberts, K., Zhuge, Q., Monga, I., Gareau, S. and Laperle, C., 2017. Beyond 100 Gb/s: capacity, flexibility, and network optimization. *Journal of Optical Communications and Networking*, *9*(4), pp.C12-C24.

Frequency Division Multiplexing



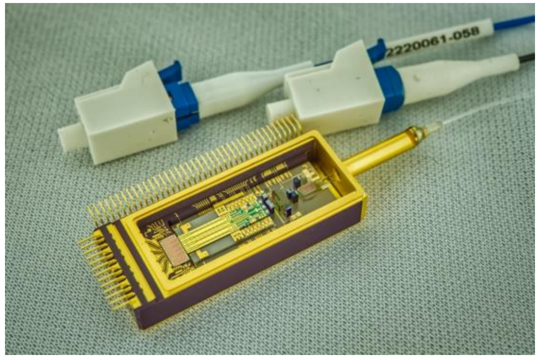


Poggiolini, P., Jiang, Y., Carena, A., Bosco, G. and Forghieri, F., 2015, March. Analytical results on system maximum reach increase through symbol rate optimization. In *2015 Optical Fiber Communications Conference and Exhibition (OFC)* (pp. 1-3). IEEE.

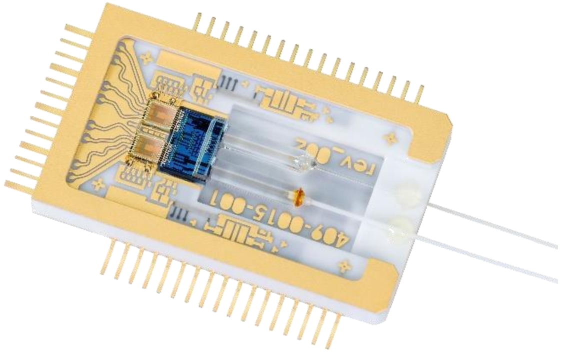
Du, L.B. and Lowery, A.J., 2011. Optimizing the subcarrier granularity of coherent optical communications systems. *OE*, *19*(9), pp.8079-8084.

WaveLogic 5e

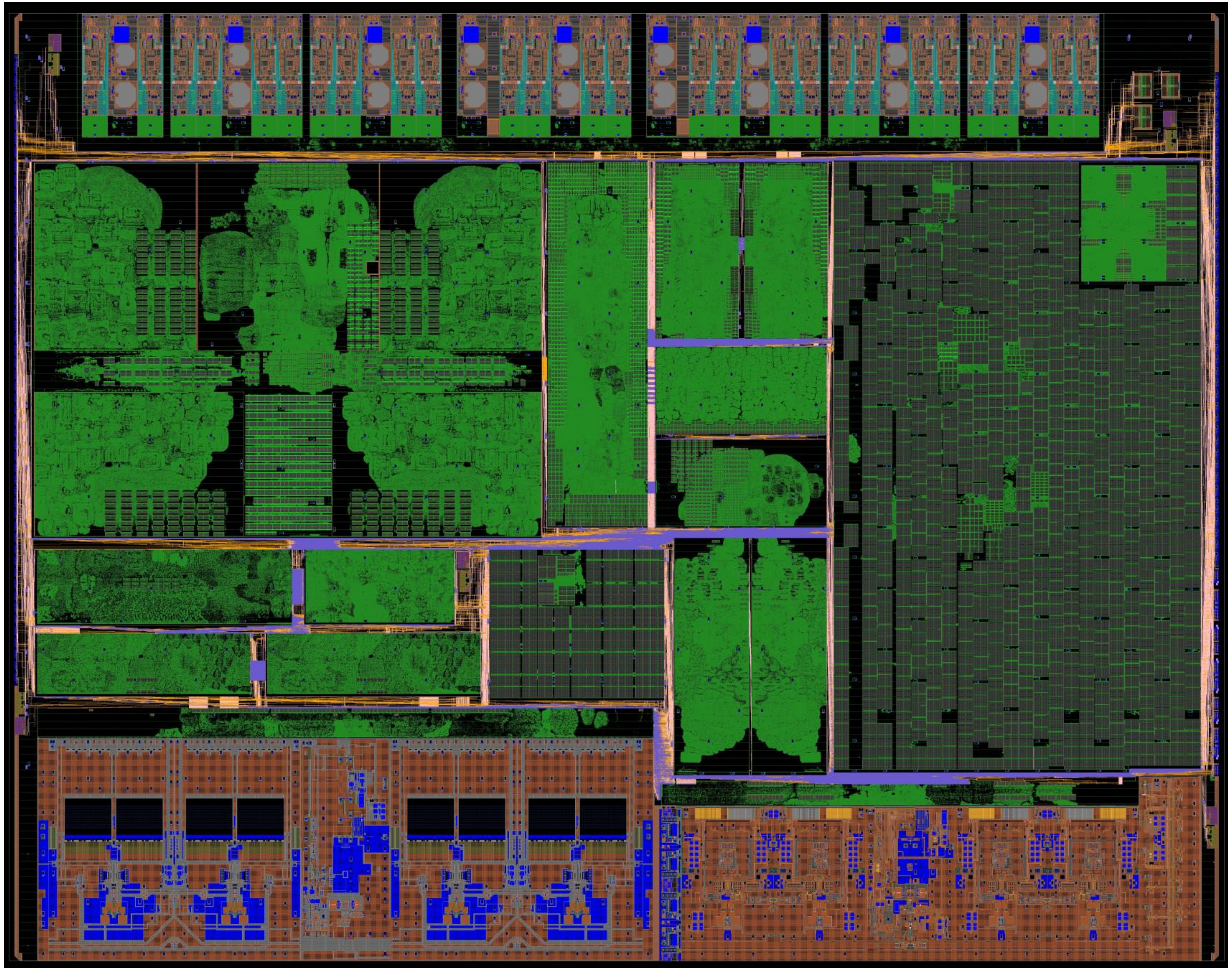
Coherent Transmitter Module



Coherent Receiver Module

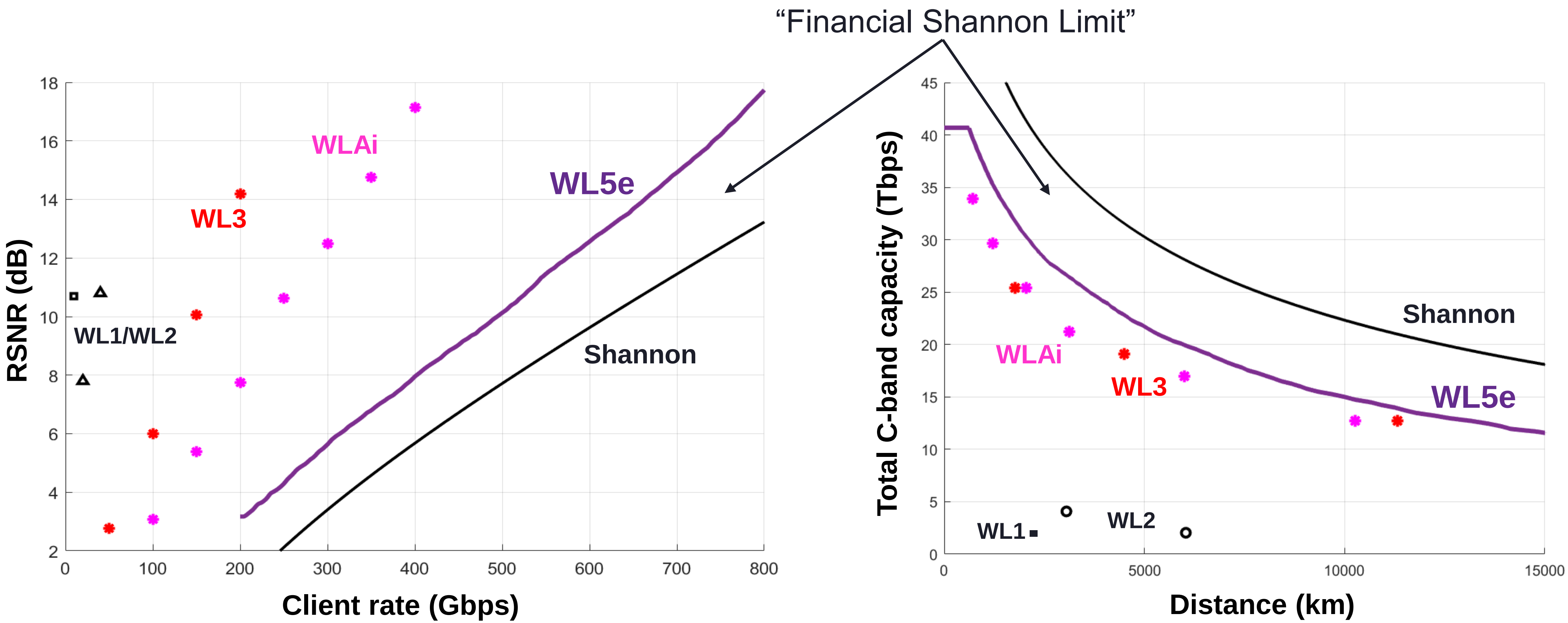


Metric	WL1	WLAi	WL5e
Mode	10G NRZ	100G QAM	800G QAM
Spectral Efficiency	0.2 b/s/Hz	6.4 b/s/Hz	7.5 b/s/Hz
Dispersion Tolerance	~1000 ps/nm	~10 ps/nm	~400,000 ps/nm
PMD Tolerance	15 ps (mean)	150 ps (mean)	150 ps (mean)



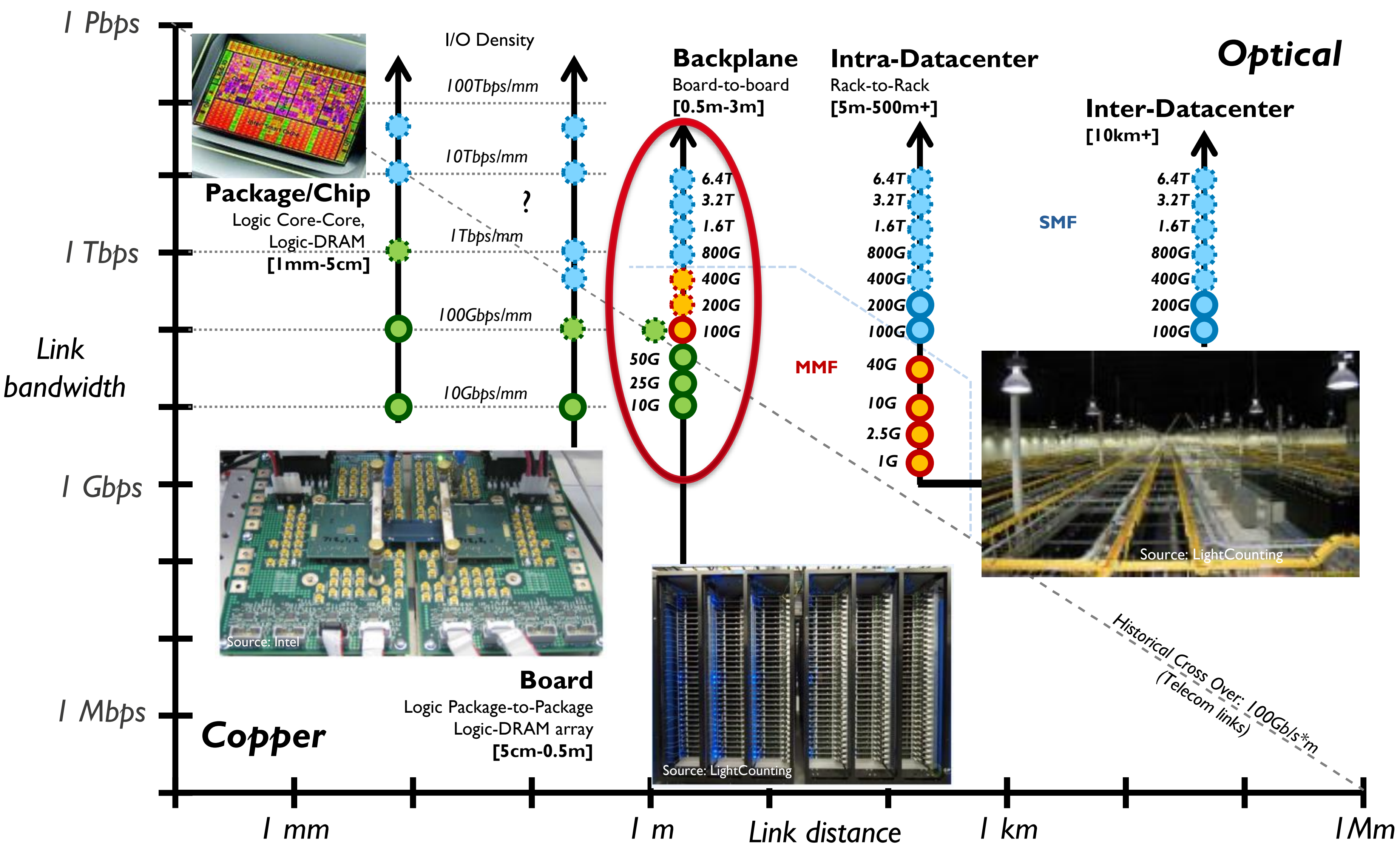
804 T ops, 7nm FinFET, 454M gates, 3.1 km of copper

WL5e Performance



Coherent Optics At Shorter Length Scales

Transition from Electrical to Optical Links



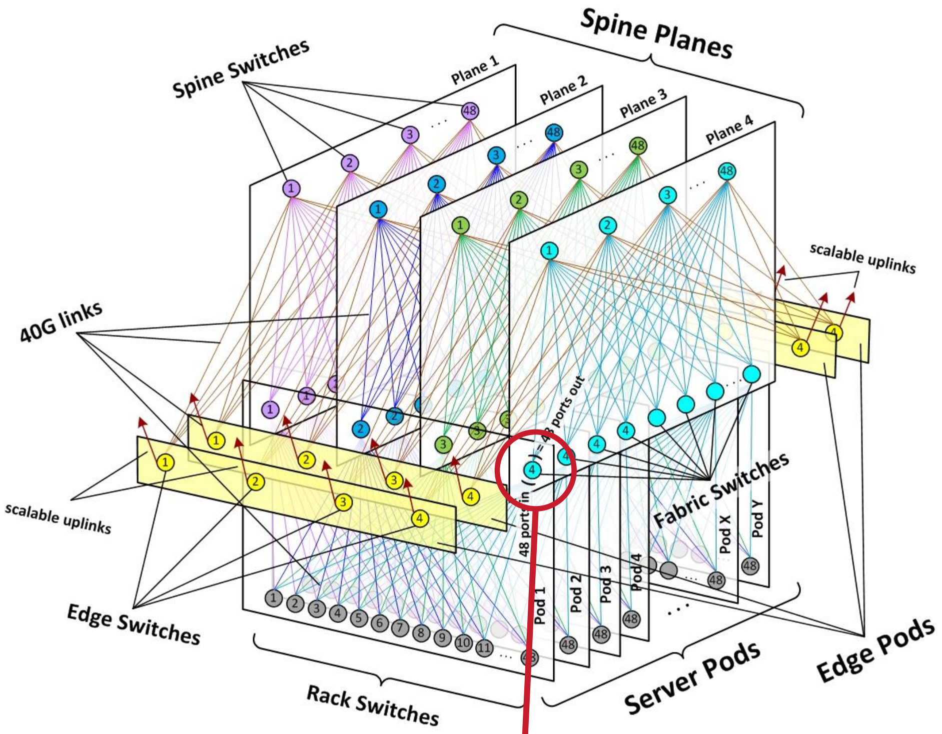
Rakowski, M.., 2017, September. Silicon photonics platform for 50G optical interconnects. In *Proc. Cadence Photon. Summit Workshop* (pp. 3-4).

TRANSITION ROADMAP (IMEC)

Optical Interconnects replacing Copper at increasingly Shorter Reach

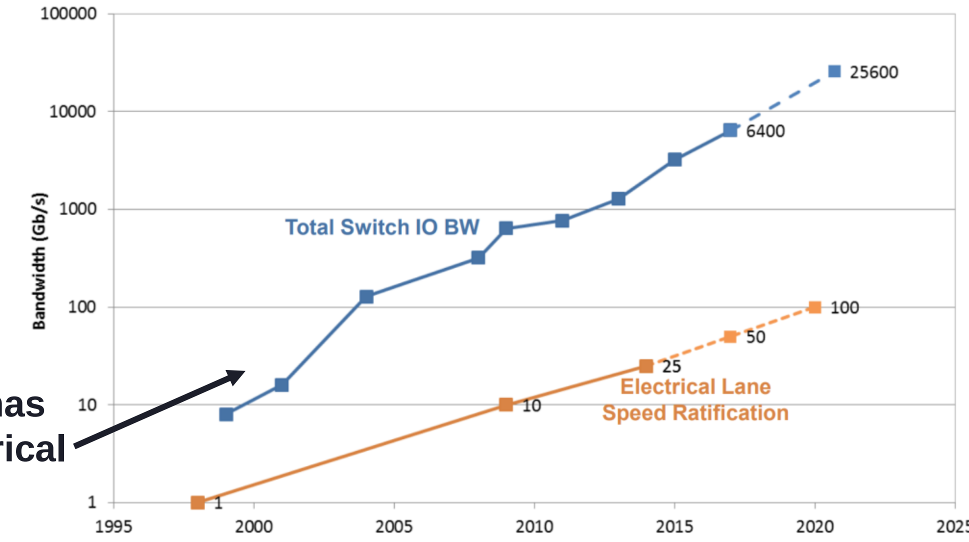
- Datacenter [5m-10km+]
  100G-400G-1.6T+
- Backplane [0.5-3m]
  8-16-32+ x ***50G-100G***
- Board [5-50cm]
  200Gbps+/mm
- Package [1cm-10cm]
  1Tbps+/mm
- Interposer/Chip [1mm-2cm]
  10Tbps+/mm

Data Center Switching

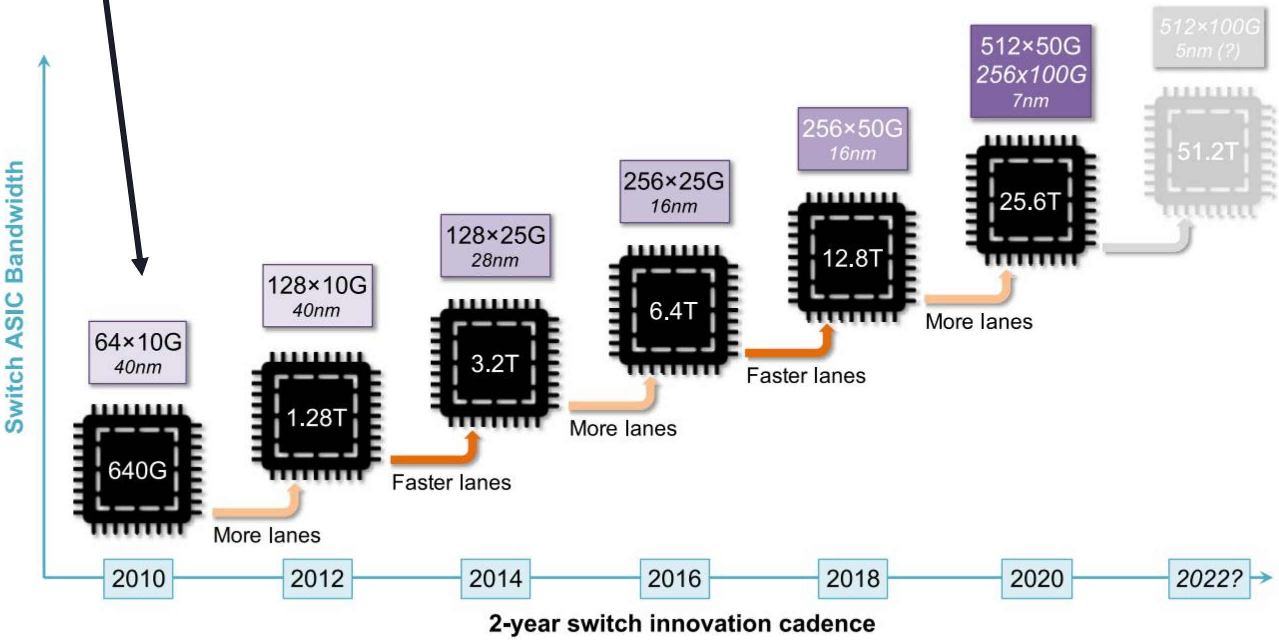


Andreyev, A., 2014. Introducing data center fabric, the next-generation Facebook data center network.

Switch IO BW has outpaced electrical lane speeds



100 Gb/s per Lane for Electrical Interfaces and PHYs. IEEE 802.3 November 7, 2017, Consensus Building



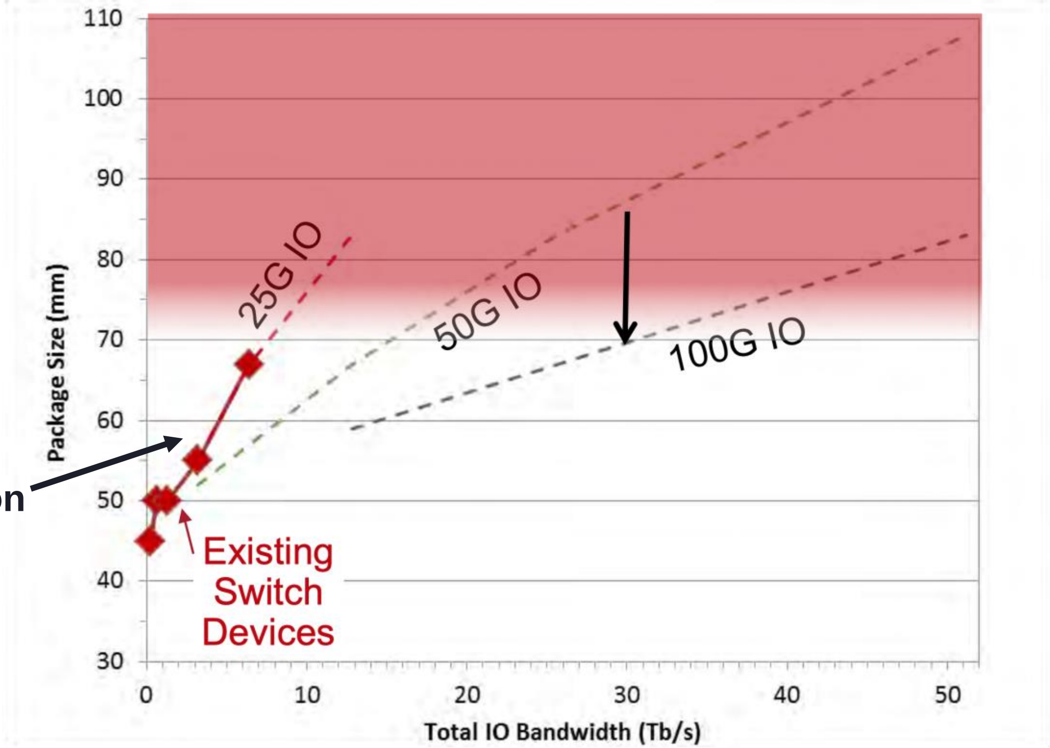
Minkenberg, C., et.al., D., 2021. Co-packaged datacenter optics: Opportunities and challenges. *IET Optoelectronics*, *15*(2), pp.77-91.

Some (of Many) Bottlenecks

Switch			Module		Faceplate	
Lanes	Rate	Capacity	Lanes	Capacity	Modules	Size
128	25G	3.2 T	4	100G	32	1RU
256	25G	6.4 T	4	100G	64	2RU
256	50G	12.8 T	8	400G	32	1RU
512	50G	25.6 T	8	400G	64	2RU
256	100G	25.6 T	8	800G	32	1RU
512	100G	51.2 T	8	800G	64	2RU
1024	100G	102.4 T	8	800G	128	4RU
1024	100G	102.4 T	16	1.6 T	64	2RU
512	200G	102.4 T	8	1.6 T	64	2RU

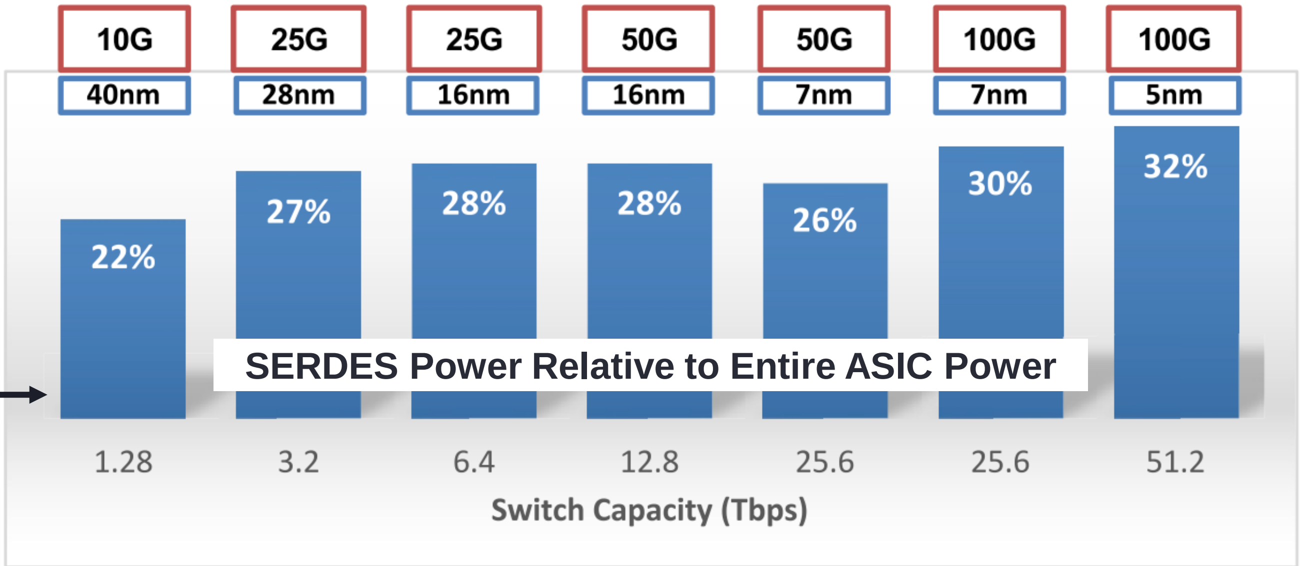
Required faceplate area increasing with each generation

Package size limits scaling with low-speed parallelization



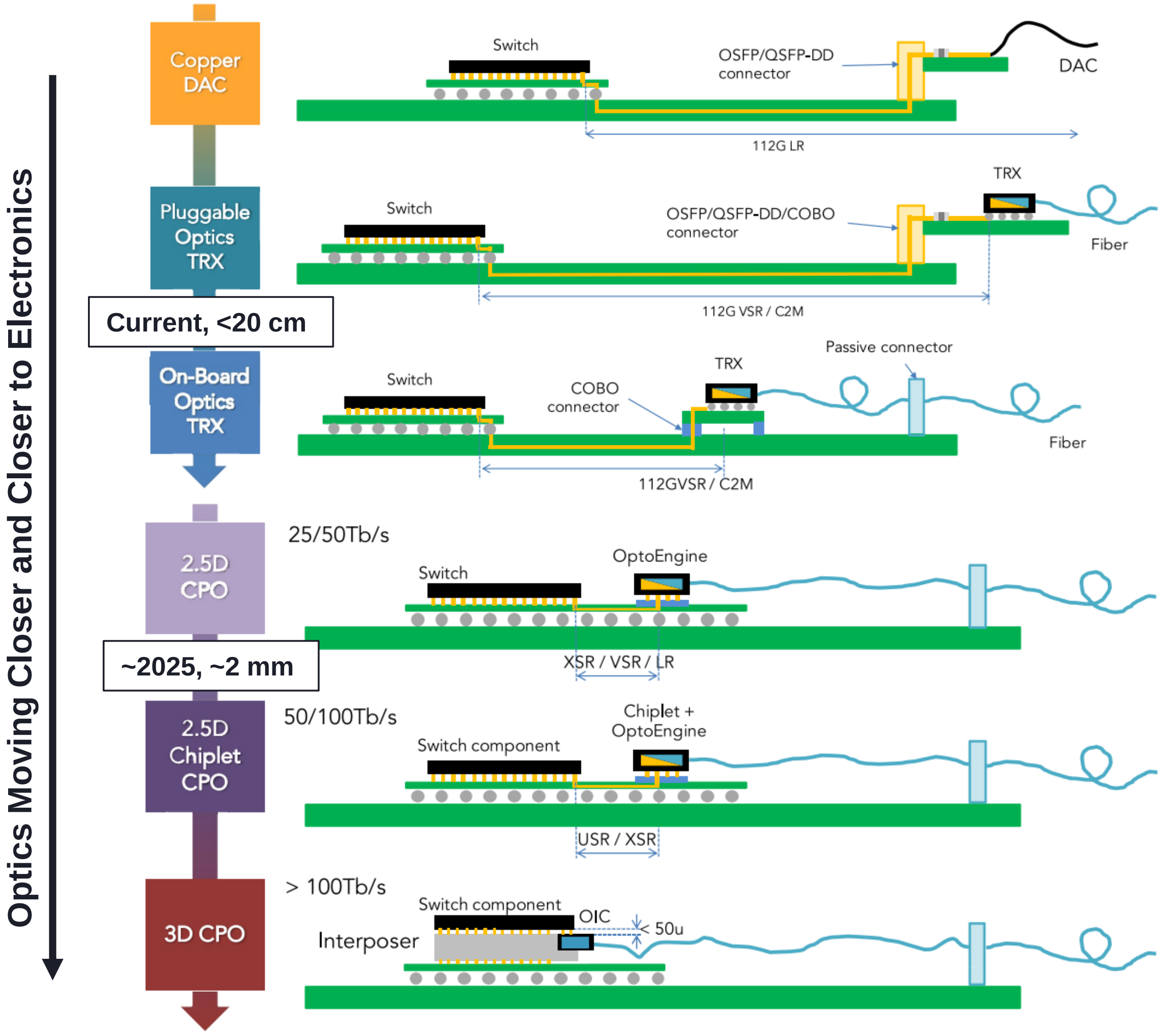
100 Gb/s per Lane for Electrical Interfaces and PHYs. IEEE 802.3 November 7, 2017, Consensus Building

Switch electrical I/O steadily increasing over time due to higher power consumption from SERDES



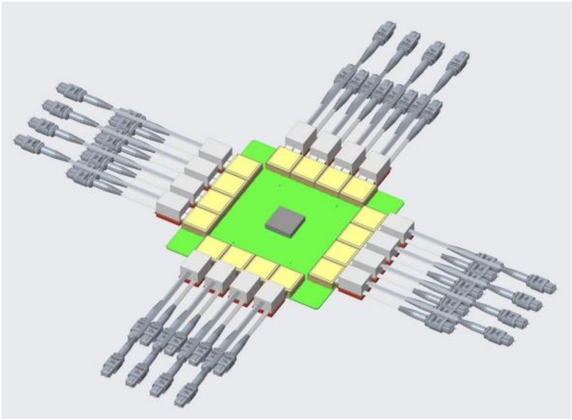
Minkenberg, C., Krishnaswamy, R., Zilkie, A. and Nelson, D., 2021. Co-packaged datacenter optics: Opportunities and challenges. *IET Optoelectronics*, *15*(2), pp.77-91.

Co-Packaging of Optics and Electronics for DC Switching

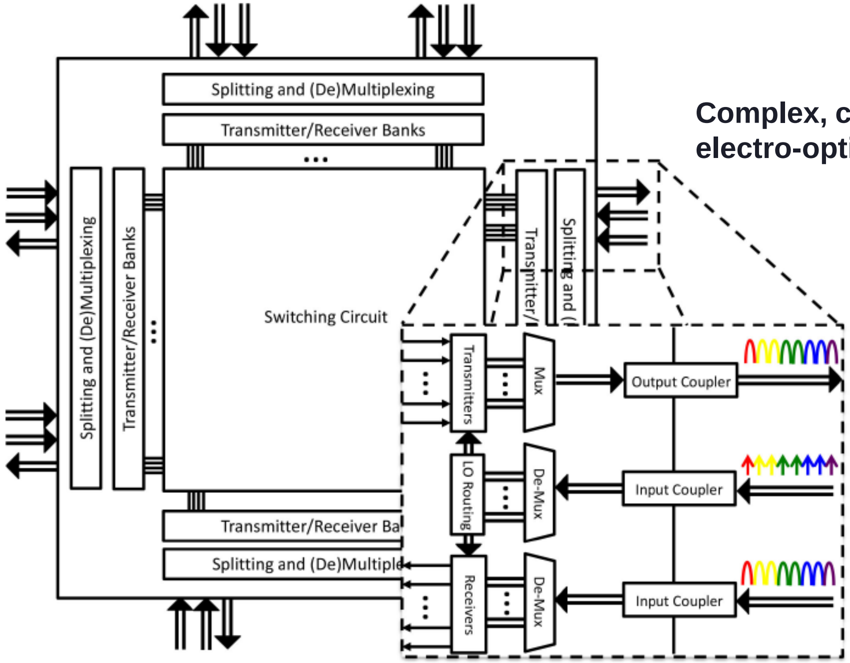


Minkenberg, C., Krishnaswamy, R., Zilkie, A. and Nelson, D., 2021. Co-packaged datacenter optics: Opportunities and challenges. *IET Optoelectronics*, *15*(2), pp.77-91.

One Proposed CPO Architecture



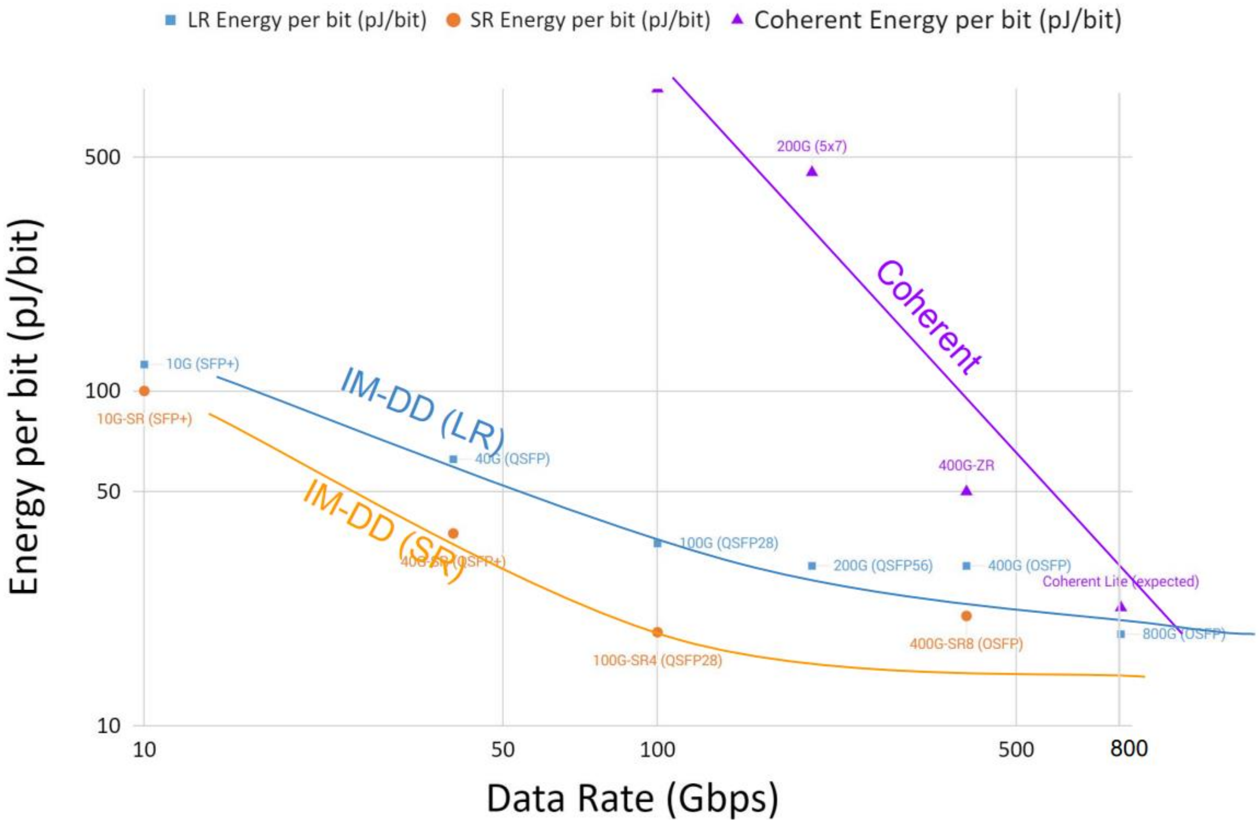
"3.2 Tb/s Copackaged Optics Optical Module Product Requirements Document", Co-Packaged Optics Collaboration, http://www.copackagedoptics.com/wp-content/uploads/2021/02/JDF-3.2-Tb_s-Copackaged-Optics-Module-PRD-1.0.pdf



Complex, compact electro-optics required

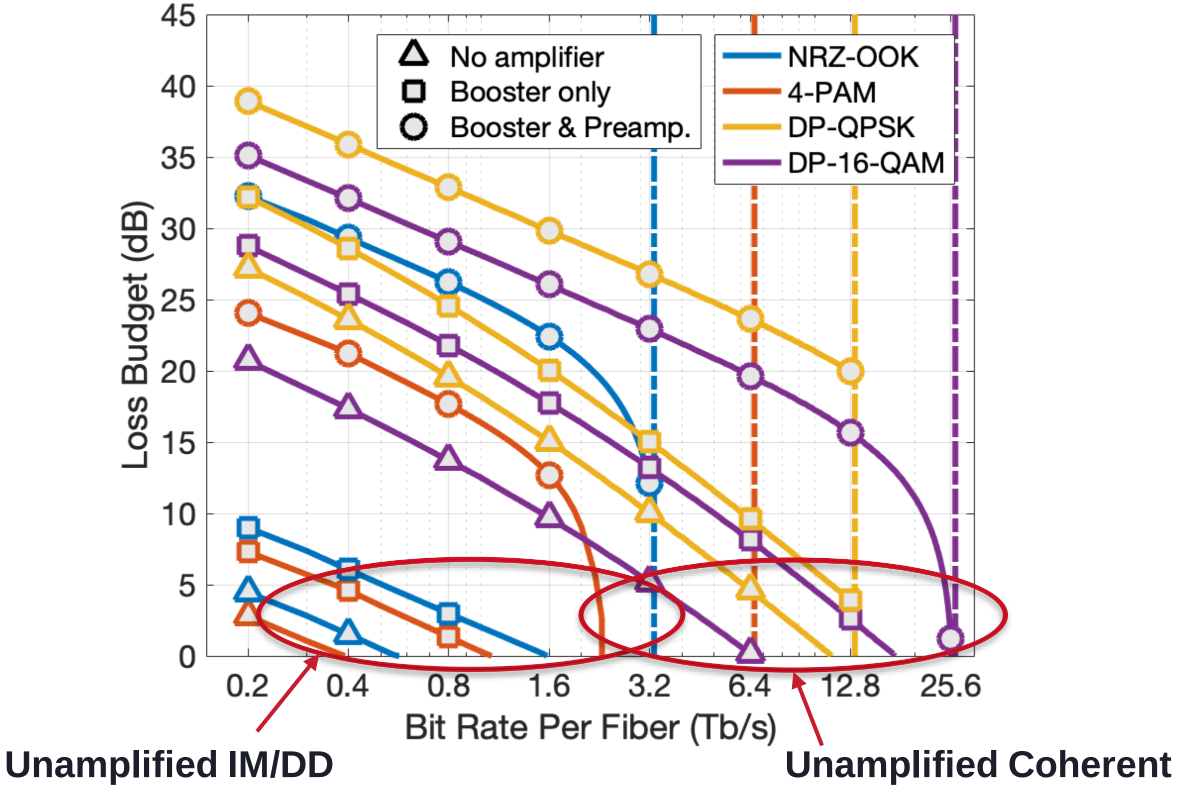
Buscaino, B., Taylor, B.D. and Kahn, J.M., 2019. Multi-Tb/s-per-fiber coherent co-packaged optical interfaces for data center switches. *Journal of Lightwave Technology*, *37*(13), pp.3401-3412.

One Solution: Coherent Intra-DC Links



"Coherent-Lite for beyond 400GbE", C.Lam, et.al. July 7, 2021, IEEE 802.3 B400G SG Meeting, https://www.ieee802.org/3/B400G/public/21_07/lam_b400g_01a_210720.pdf

Performance Comparison

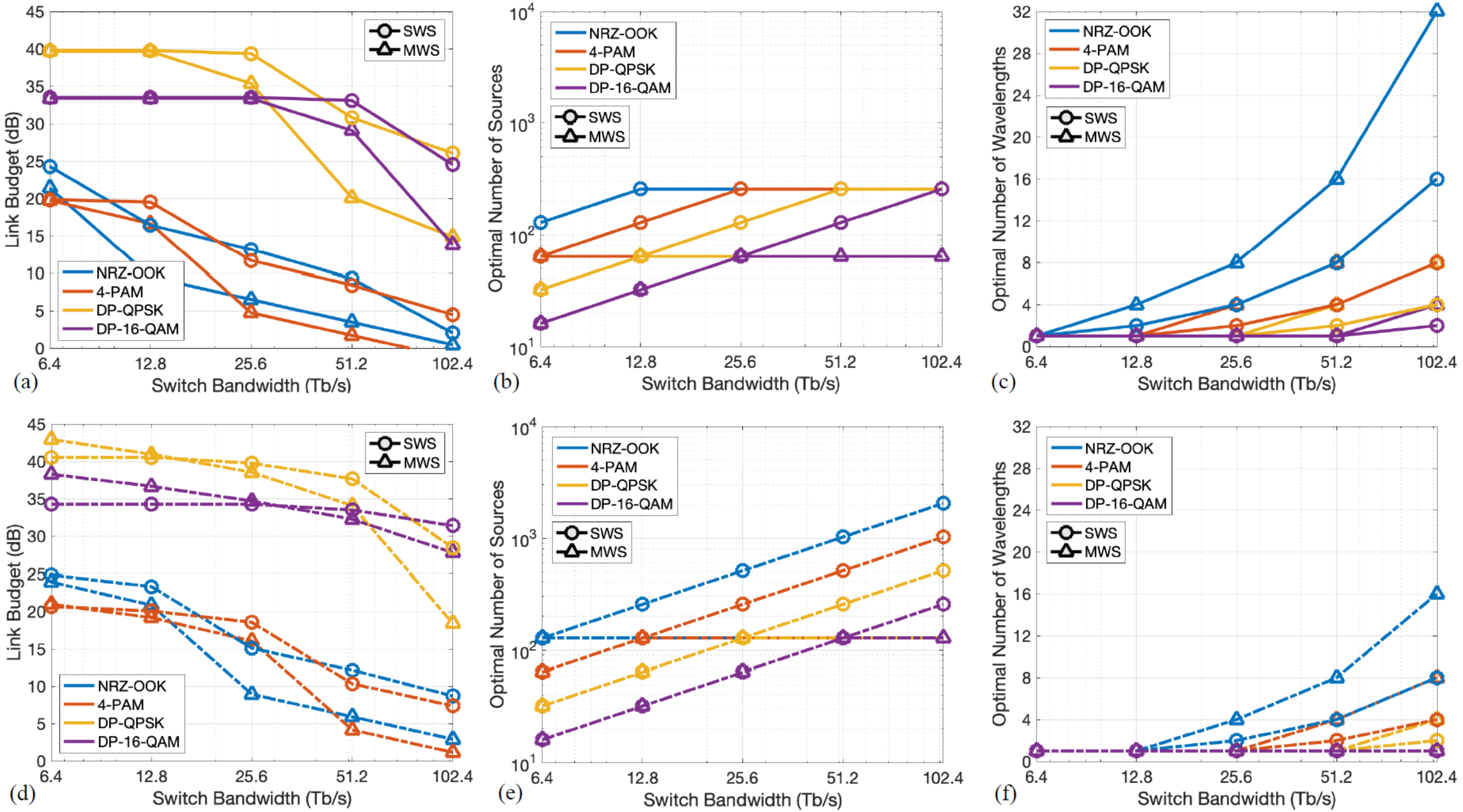


Buscaino, B., Taylor, B.D. and Kahn, J.M., 2019. Multi-Tb/s-per-fiber coherent co-packaged optical interfaces for data center switches. *Journal of Lightwave Technology*, *37*(13), pp.3401-3412.

External vs Integrated Light Sources for Co-Packaged Optics

External Light Sources

Integrated Light Sources



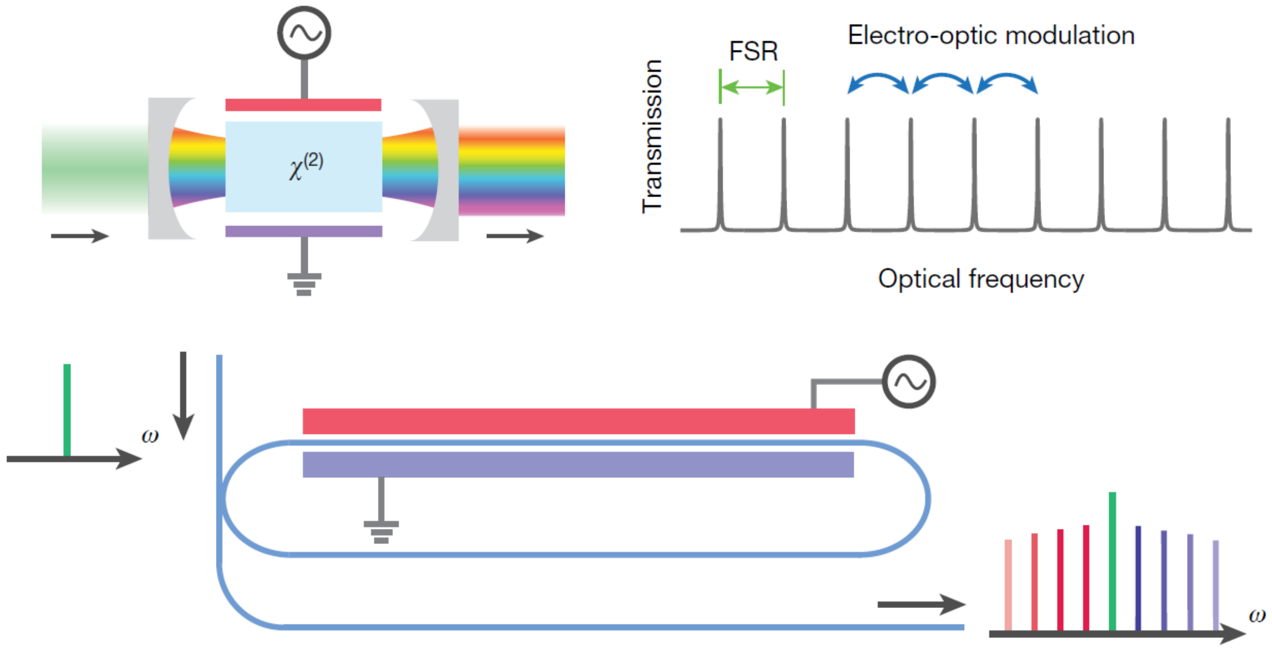
Buscaino, B., Chen, E., Stewart, J.W., Pham, T. and Kahn, J.M., 2020. External vs. integrated light sources for intra-data center co-packaged optical interfaces. *Journal of Lightwave Technology*, *39*(7), pp.1984-1996.

ciena

Electro-Optic Frequency Combs and Data Center Links

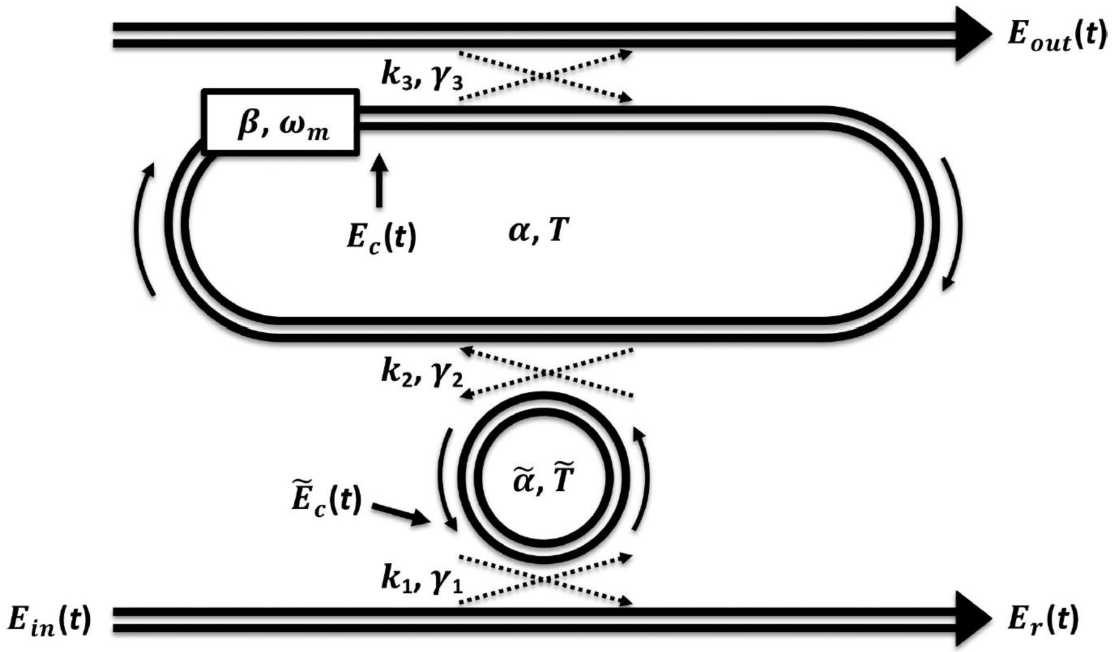
Electro-Optic Frequency Comb Generation

Single-Resonator EO Comb Generation



Zhang, M., Buscaino, B., Wang, C., Shams-Ansari, A., Reimer, C., Zhu, R., Kahn, J.M. and Lončar, M., 2019. Broadband electro-optic frequency comb generation in a lithium niobate microring resonator. *Nature*, *568*(7752), pp.373-377.

Dual-Resonator EO Comb Generation



Buscaino, B., Zhang, M., Lončar, M. and Kahn, J.M., 2020. Design of efficient resonator-enhanced electro-optic frequency comb generators. *Journal of Lightwave Technology*, *38*(6), pp.1400-1413.

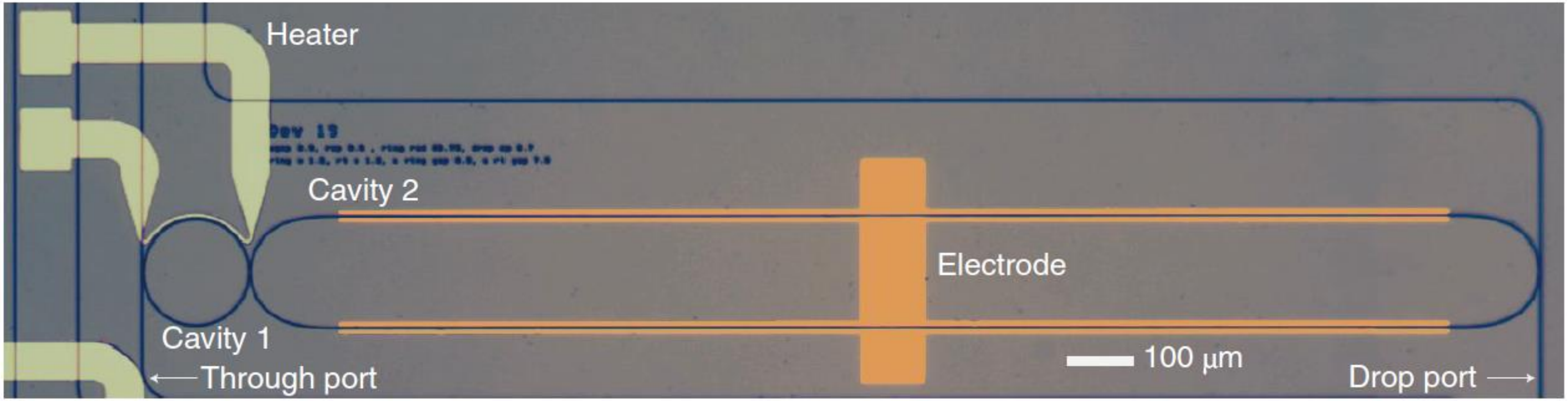
Comb spectrum can be solved for with numerical methods and the following steady-state assumption:

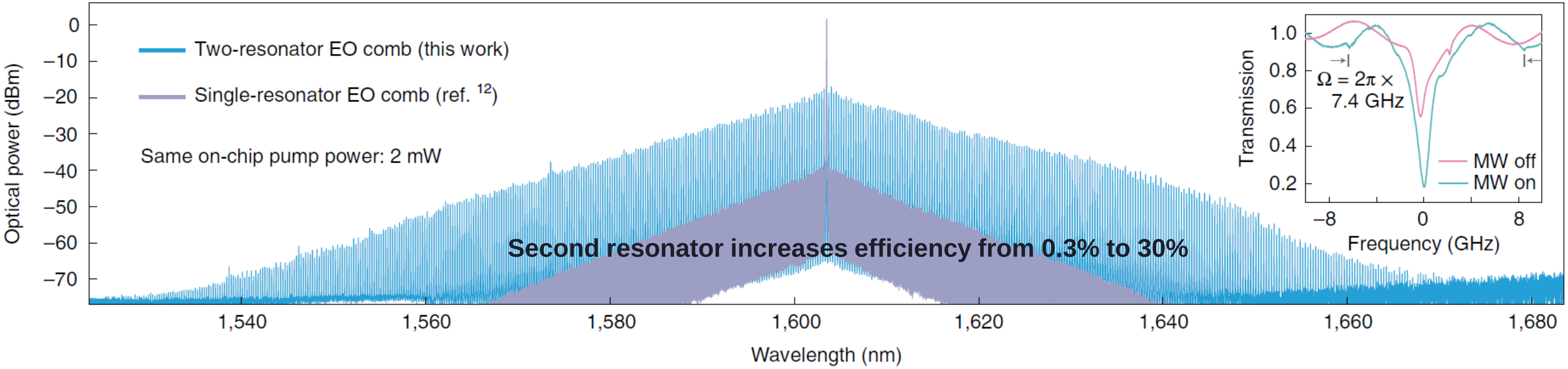
$$E_c(t) = \sum_{p=-\infty}^{\infty} E_p e^{i(\omega_0 + p\omega_m)t}$$

Dual-Resonator EO Comb Generator Intra-Resonator Field Relation

$$E_p = \sum_{p=-\infty}^{\infty} r' J_q(\beta) e^{i\omega_{p-q}T} \left(\frac{1 - \tilde{r}' e^{i\omega_{p-q}\tilde{T}}/(1-k_2)}{1 - \tilde{r}' e^{i\omega_{p-q}\tilde{T}}} \right) E_{p-q} - (\alpha\tilde{\alpha})^{1/4} \sqrt{(1-\gamma_1)k_1(1-\gamma_2)k_2} \times J_p(\beta) e^{i\omega_0(T/2+\tilde{T}/2)} \left(\frac{1}{1 - \tilde{r}' e^{i\omega_0 \tilde{T}}} \right),$$

High-Efficiency Integrated EO Comb Generation

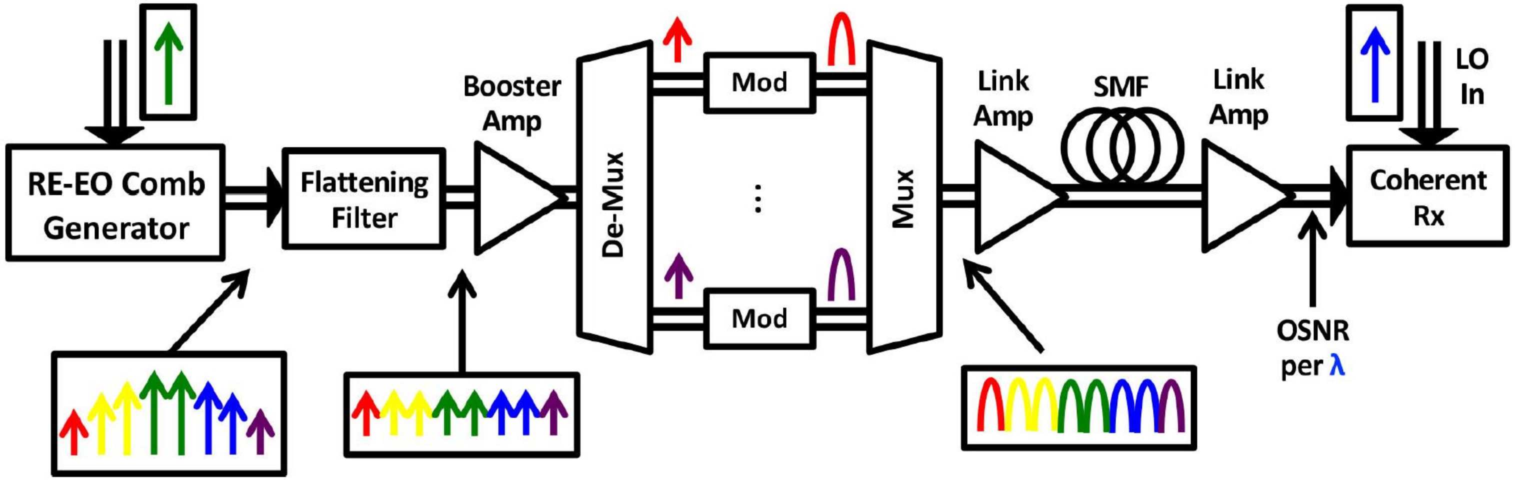




Second resonator increases efficiency from 0.3% to 30%

Hu, Y., Yu, M., Buscaino, B., Sinclair, N., Zhu, D., Cheng, R., Shams-Ansari, A., Shao, L., Zhang, M., Kahn, J.M. and Lončar, M., 2022. High-efficiency and broadband on-chip electro-optic frequency comb generators. *Nature Photonics*, *16*(10), pp.679-685.

EO Comb Generators for Inter-Data Center Links



WDM LINK PARAMETERS

Input laser power	20 dBm
Insertion loss from output-coupling and flattening	5 dB
Booster amplifier noise figure	5 dB
Booster amplifier gain*	30 dB
Insertion loss from (de-)multiplexing and modulation	20 dB
Link amplifier noise figure	5 dB
Link amplifier gain	20 dB
Insertion loss from SMF	20 dB
Local oscillator power	15 dBm

*20 dB for dual-ring RE-EO comb generator

ROSNR for 28 GBd DP-16-QAM: ~22 dB

OSNR with single-resonator EO comb generator: ~21 dB

OSNR with dual-resonator EO comb generator: ~28 dB

Assuming 100 channels spaced at 50 GHz, maximum bit rate per fiber is 20 Tb/s for a 100 km SMF link

Note: This architecture most compatible with point-to-point topology

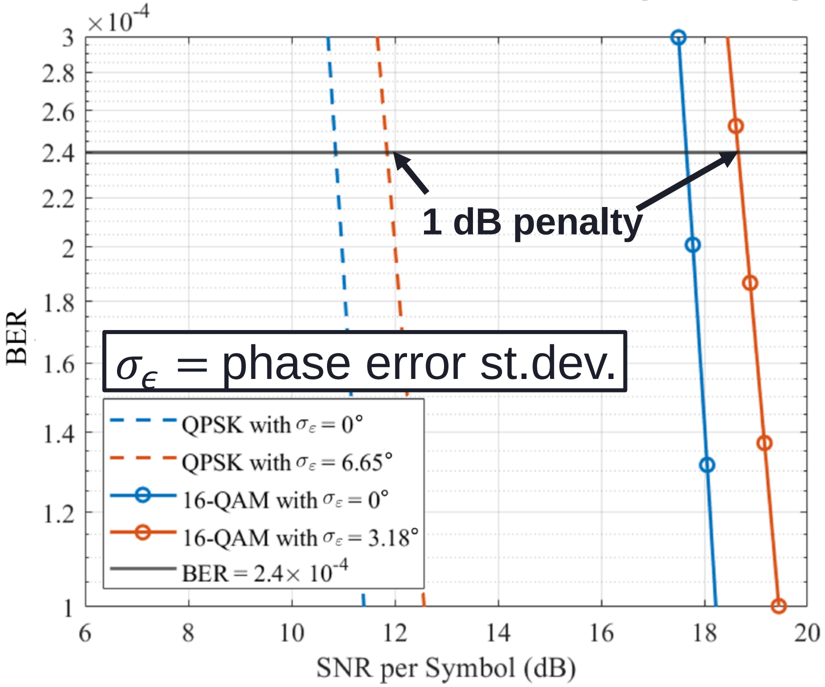
Buscaino, B., Zhang, M., Lončar, M. and Kahn, J.M., 2020. Design of efficient resonator-enhanced electro-optic frequency comb generators. *Journal of Lightwave Technology*, *38*(6), pp.1400-1413.

Low-Power Analog Coherent Inter-Data Center Links

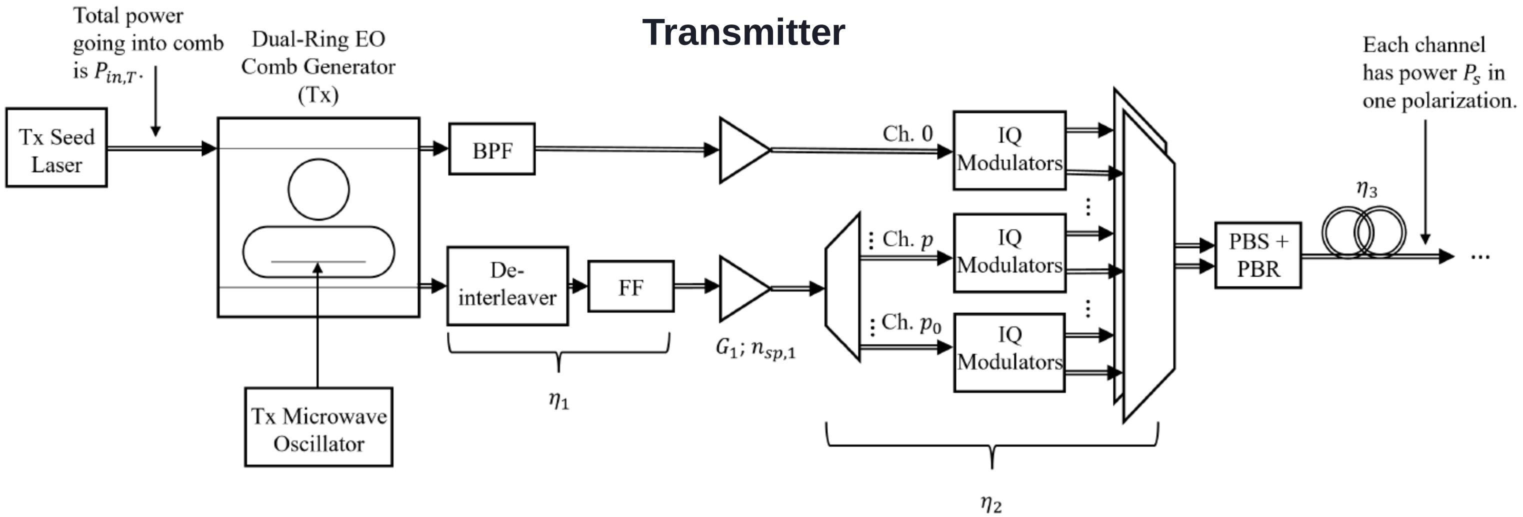
Central idea: Use an EO comb generator as the transmitter laser and receiver local oscillator

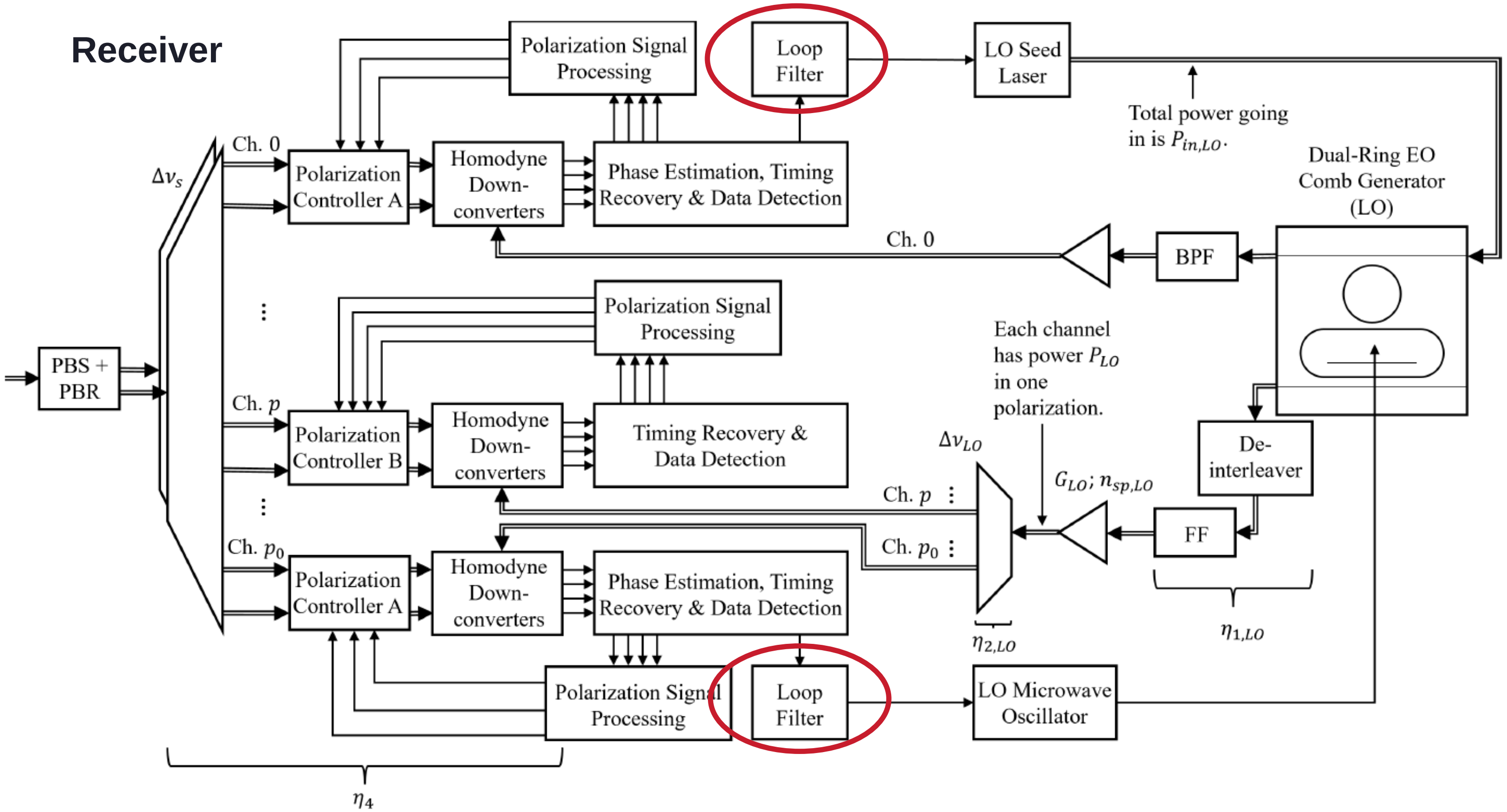
Requires only two phase-locked loops for link composed of 17 56 GBd DP-16-QAM channels on 15 km SMF, resulting in net bit rate of 6.8 Tb/s

RSNR @ BER = 2.4×10^{-4}, RS(544, 514)

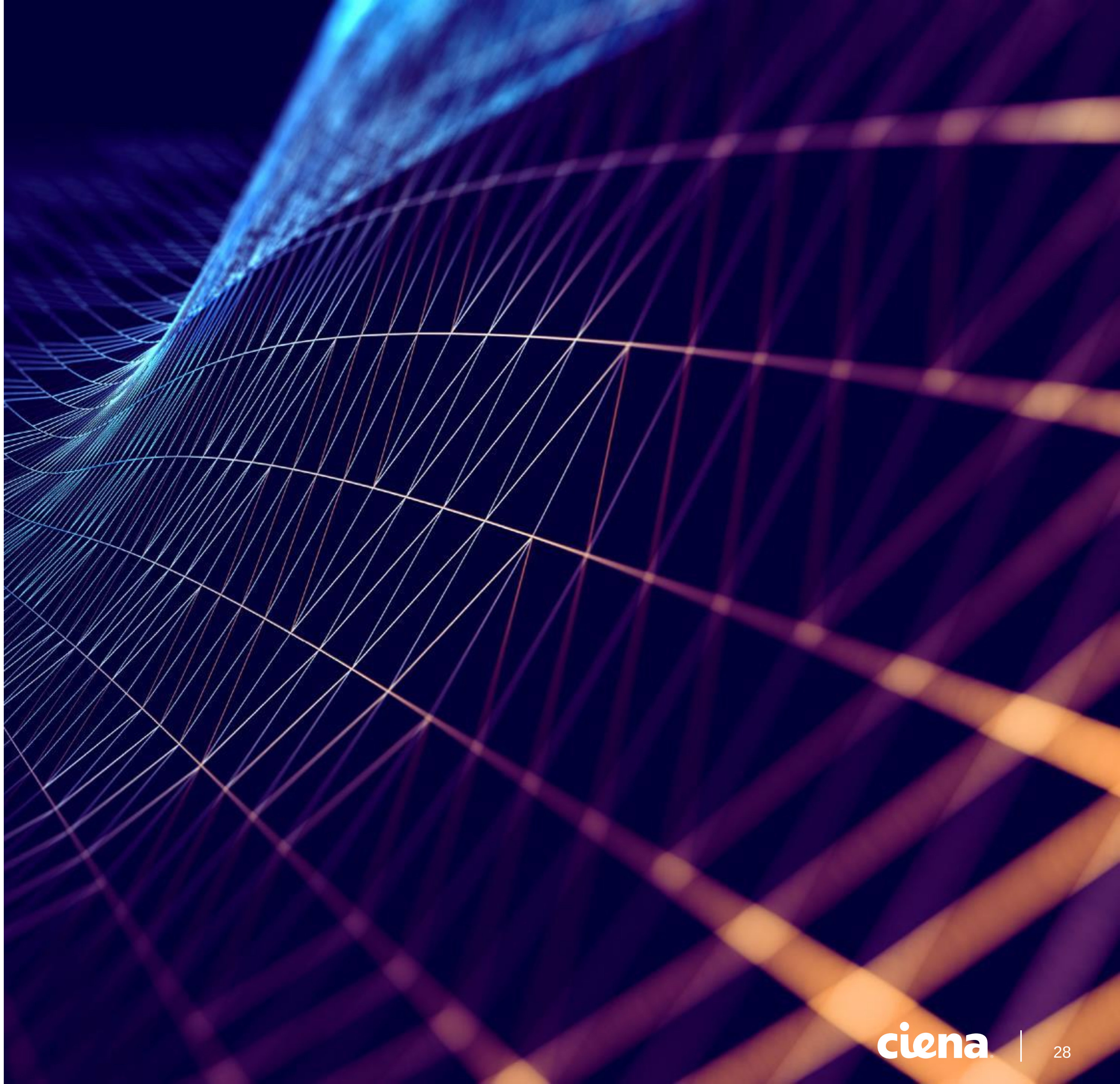


Chen, E., Buscaino, B. and Kahn, J.M., 2022. Phase Noise Analysis of Resonator-Enhanced Electro-Optic Comb-Based Analog Coherent Receivers. *Journal of Lightwave Technology*.





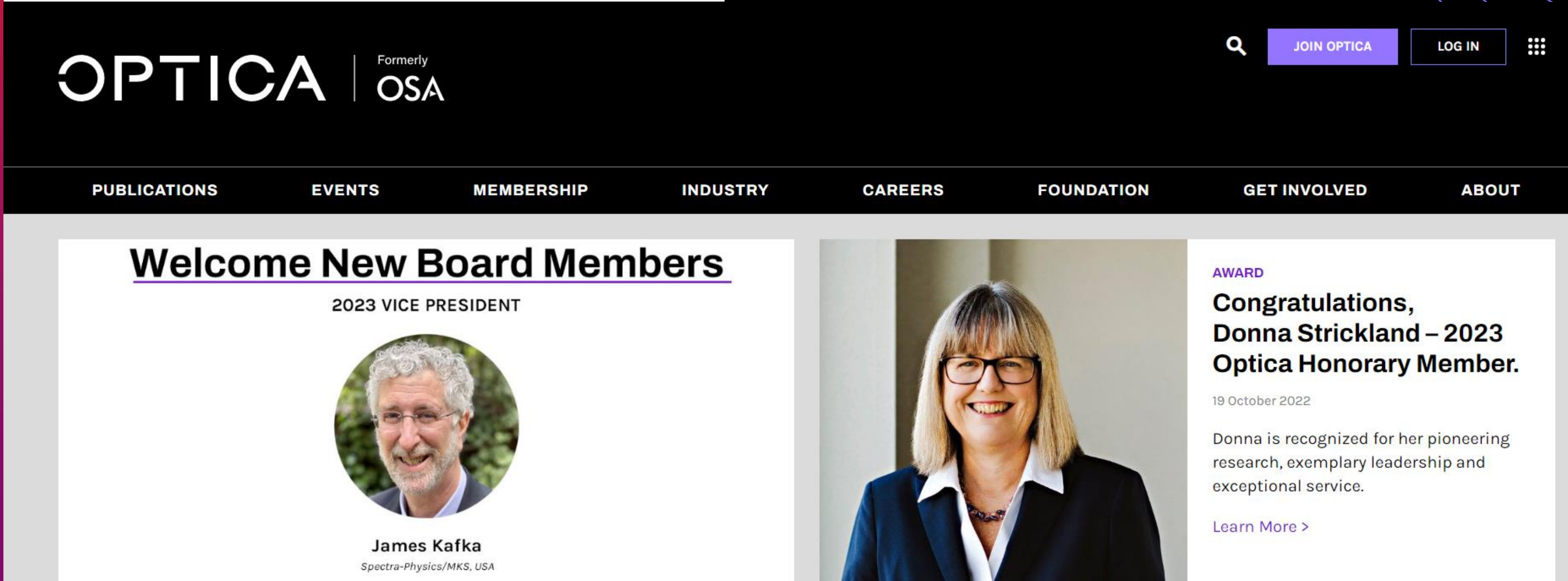
Professional Development: Optica Resources and Student Opportunities



OPTICA and OPTICA Foundation Resources

https://www.optica.org/en-us/home/

OPTICA
Advancing Optics and Photonics Worldwide



Optica Foundation Programs for Students

Scholarships

- Optica Women Scholarship
- Amplify Scholarship
- Boris P. Stoicheff Memorial Scholarship
- Corning Women in Optical Communications Scholarship
- Bonenfant International Travel Scholarship
- Harvey M. Pollicove Memorial Scholarship

Prizes and Competitions

- Maiman Student Paper Competition (CLEO)
- Wolf Outstanding Student Paper Competition (FiO+LS)
- Corning Outstanding Student Paper Competition (OFC)

Travel Grants

- Corning Women in Optical Communications Travel Grant
- FiO+LS Incubic Milton Chang Travel Grant
- CLEO Incubic Milton Chang Travel Grant
- Jean Bennett Memorial Student Travel Grant
- Robert S. Hilbert Memorial Student Travel Grant

Learning

- The Siegman International School on Lasers
- Career Accelerator
- Subsea Optical Fiber Communications School
- The Innovation School
- Career Calibrator
- Traveling Lecturer Program
- Mentor Match

Optica Foundation Resources for Early-Career Professionals

Fellowships

- Chang Pivoting Fellowship
- Deutsch Fellowship

Prizes and Competitions

- Kaminow Outstanding Early Career Professional Prize
- Li Innovation Prize (CLEO)
- Li Innovation Prize (OFC)
- Couillaud Prize
- Theodor W. Hänsch Prize in Quantum Optics
- Adolph Lomb Medal
- Kevin P. Thompson Optical Design Innovator Award

Ambassador Program

- Ambassador applications close on Nov 16, 2022!

Learning

- Career Accelerator
- The Innovation School
- Optica Technical Groups

Career

- The Career Lab
- Career Calibrator
- WORKinOPTICS
- Optica Local Sections

Outreach and Public Policy

Outreach

- Optics for Kids
- Optics at Home
- Optics Suitcase
- Education and Training in Optics and Photonics
- PBL: Teaching and Learning Optics With Inexpensive Materials
- Educational Posters
- Women in STEM Challenge

Public Policy

- Global Environmental Measurement and Monitoring Initiative (GEMM)
- Global Health Initiative
- Advocate of Optics Program
- Coalitions and Advocacy
- Policy Issue Positions

U.S. Public Affairs Programs

- Capitol Hill Visits
- District Visits
- Congressional Fellowships
- Congressional Optics & Photonics Caucus
- National Photonics Initiative
- Write Your Representative

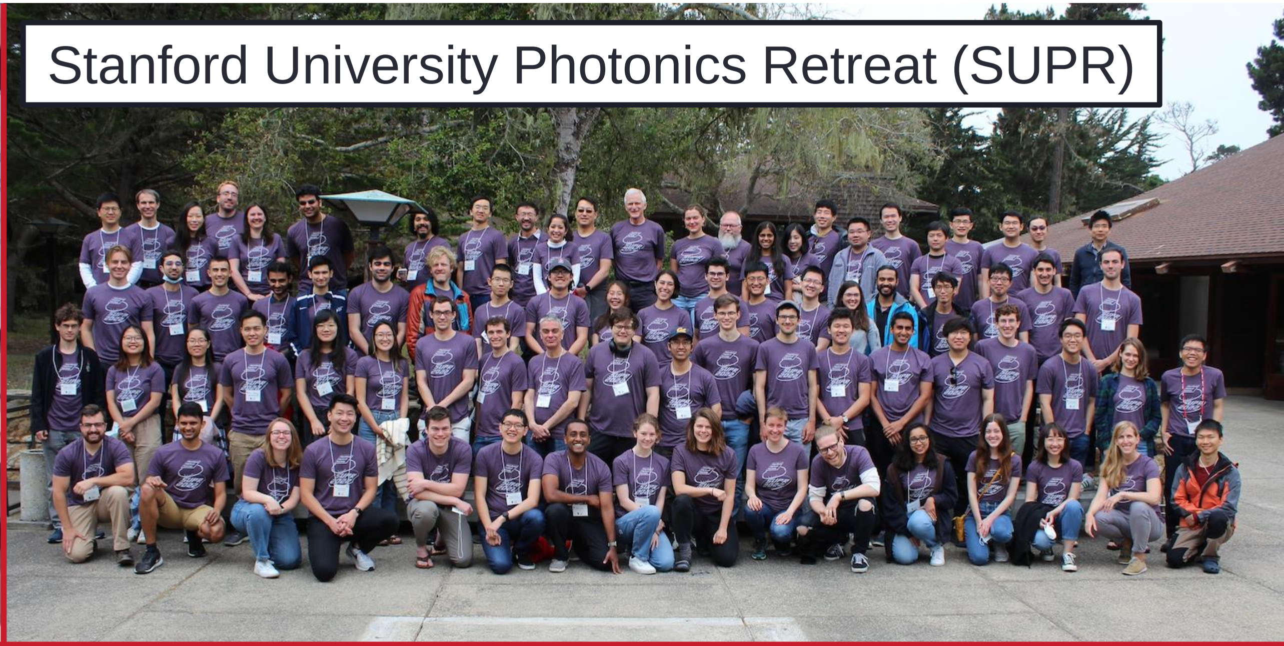
Student Chapters

Student Chapter Benefits

- Chapter Funding
- IONS+
- Chapter Toolkit
- Traveling Lecturer Program
- Student Leadership Experience

Stanford Optical Society


Speakers Committee


Stanford University Photonics Retreat (SUPR)


Outreach Committee


Membership Committee

General Advice for Graduate Students and Early-Career Professionals

Graduate Students

- Be open to trying new projects and exploring new ideas - this might get harder in the future.
- Try to focus on one thing at a time - working on multiple projects at once can really slow you down.
- Be open and honest with your PI. Many disagreements between students and PIs can be resolved by simple communication.
- Try out an internship! The industry experience will help you regardless of future paths.

Early-Career Professionals

- Continually ask for advice from your manager. In many cases soliciting feedback is the only way to become a better engineer or scientist.
- Seek out mentors in all aspects of your life. Having a support network will benefit you greatly in the future.
- Try to learn the structure of your company early and meet as many people as possible.
- Ask questions early and frequently!

Thank You!

Please reach out if you have questions or comments

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My thanks to the many people who contributed to the content of these slides, including:

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- Joseph M. Kahn Group, Stanford
- Marko Loncar Group, Harvard

Ciena is an industry-leading, global networking systems, services, and software company – Check out our Careers Page!

$3.5B Annual Revenue	**8.0%** 3YR CAGR	**$1.3B** Cash Position	**#1 or #2[1]** Market Position
35+ Countries	**7,000+** Employees	**1,700+** Customers	**Strong[2]** Governance Practices

Note: As of FYE or for FY 2020.
[1] As cited by Omdia, Dell'Oro Group and Cignal AI for different markets.
[2] ISS QualityScore of 1 (out of 10) - Bloomberg