Breaking through the DCI data rate barrier

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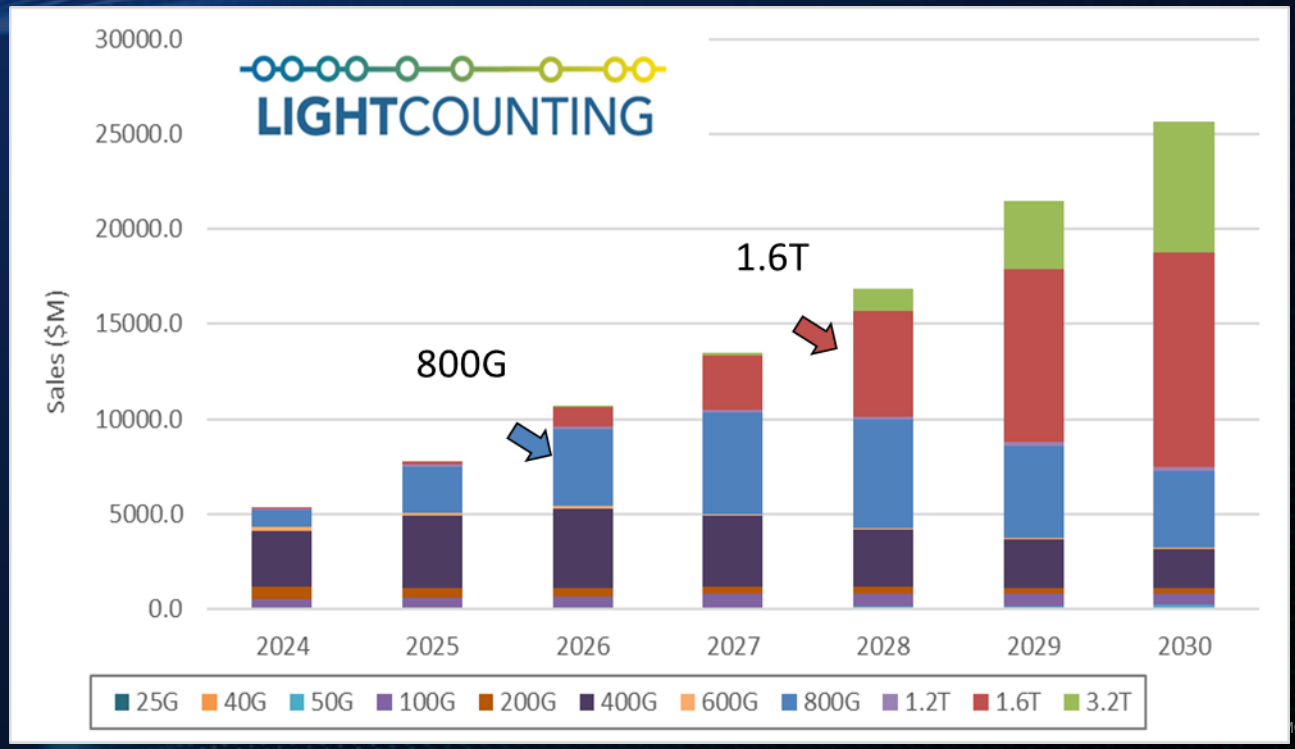
Is there a data rate scaling law equivalent to Moore's law for CMOS scaling?

- You bet there is. In fact there are two such laws I managed to find.
  1. Edholm's Law of Bandwidth: Telecommunication bandwidth doubles approximately every 18 months.
  2. Nielsen's Law of Internet Bandwidth: Bandwidth capacity roughly doubles every 21 months.

- What does this mean for DCI's (data center interconnects): Roughly every a year and a half to two years, the capacity/module doubles.

bandwidth capacity	peak market adoption
10G to 40G	2018~2022
100G	2020~2024
400G	2023~2026
800G	2025~2028
1.6T and beyond	2025+

per Gemini



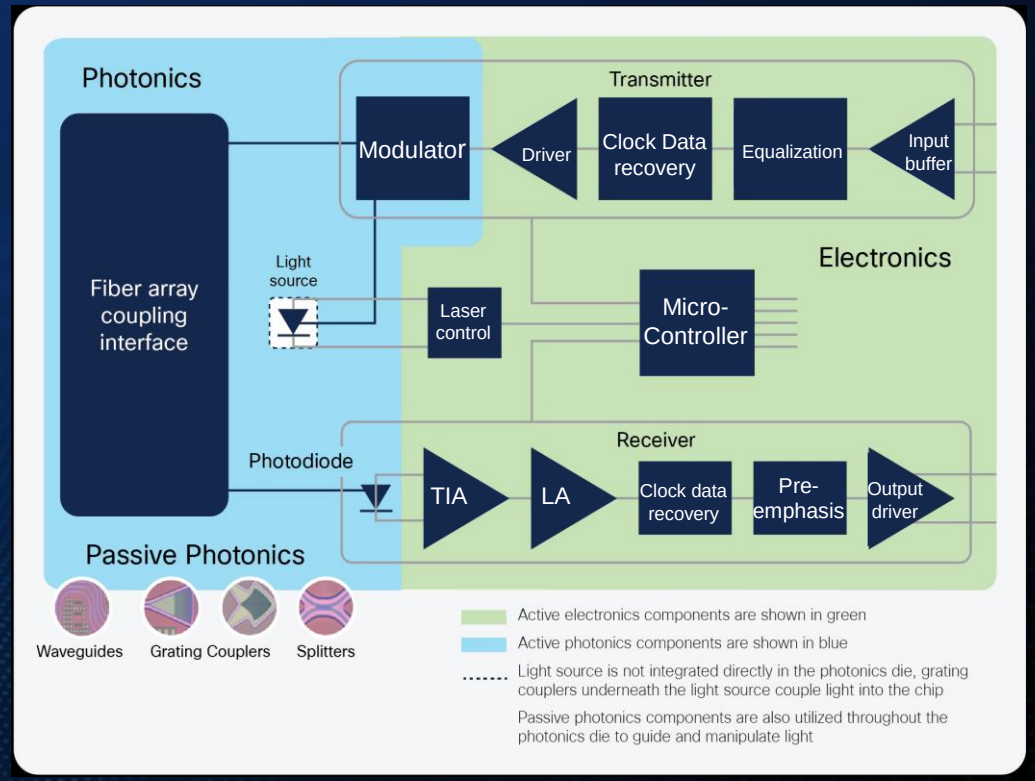
Challenges from higher data rates

- In this presentation we focus on the scaling trend of DCI's date rate/channel, not per module, and on the photonic part of the transceivers.

- Critical components in an electrical-optical transceiver:
  - The modulator
  - The DSP/SERDES
  - EIC: TIA and driver
  - The photo diode

- 200 Gbps/channel already happened. The most common configuration:
  - PAM4
  - Si MZM (DFB laser)
  - Ge PD
  - SiGe BiCMOS TIA/driver
  - Advanced logic DSP/SERDES
  - IM/DD, single-wavelength

- 400 Gbps/channel in demo status, facing many challenges, as almost every component seems shaky at such data rate.
  - Si modulators out of steam
  - Ge PD bandwidth very marginal
  - Bipolar transistors need to reach 500 GHz f_T for TIA/driver
  - DSP/SERDES extremely difficult to design



Courtesy of Cisco

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Can this scaling trend go on forever?

- The scaling trend is not likely to continue in a brute-force manner. Both electronics and optics face stiff challenges at 400 Gbps/channel and above.
  - SERDES facing CMOS performance limitation.
  - On optical side both photo diodes and Si modulators face bandwidth limitations.
    - 400 Gpbs/channel (PAM4) requires > 110 GHz electrical 3-dB bandwidth!

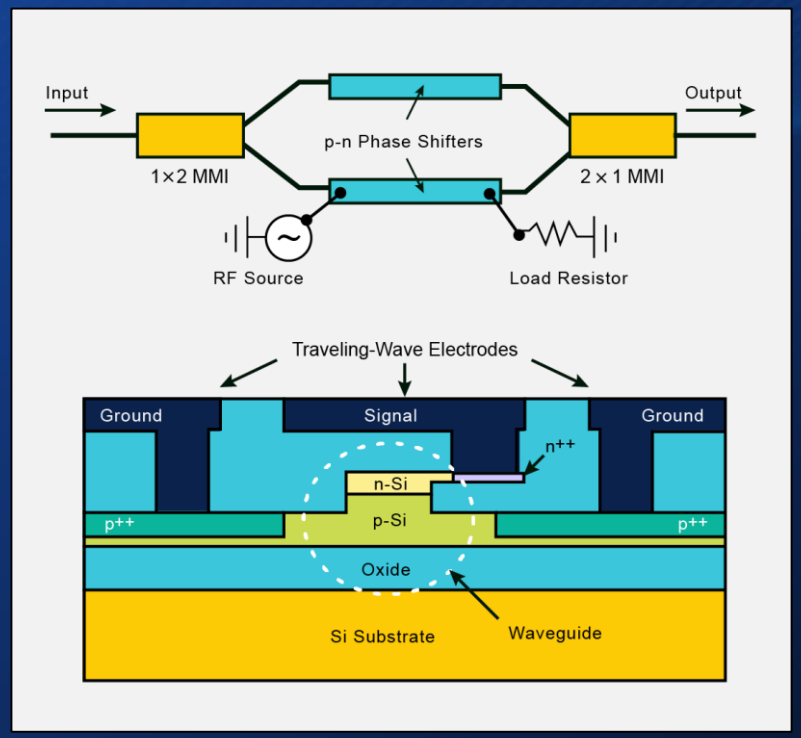
- 300 Gbps/channel a “bridging” data rate spec

- Paths to higher data rates (400 Gbps/channel and above):
  - PAM4 -> PAM8
  - Adopting components with higher bandwidth
  - Coherent transmission
  - WDM: multiple wavelengths per channel
  - A combination of the above

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Modulator selection

- Modulator – maybe the most critical device of the photonic technology.
- Si and SiGe modulators:
  1. MZM:



Courtesy of Photonic Spectra

Table 1. State-of-the-art high bandwidth all-silicon MZMs.

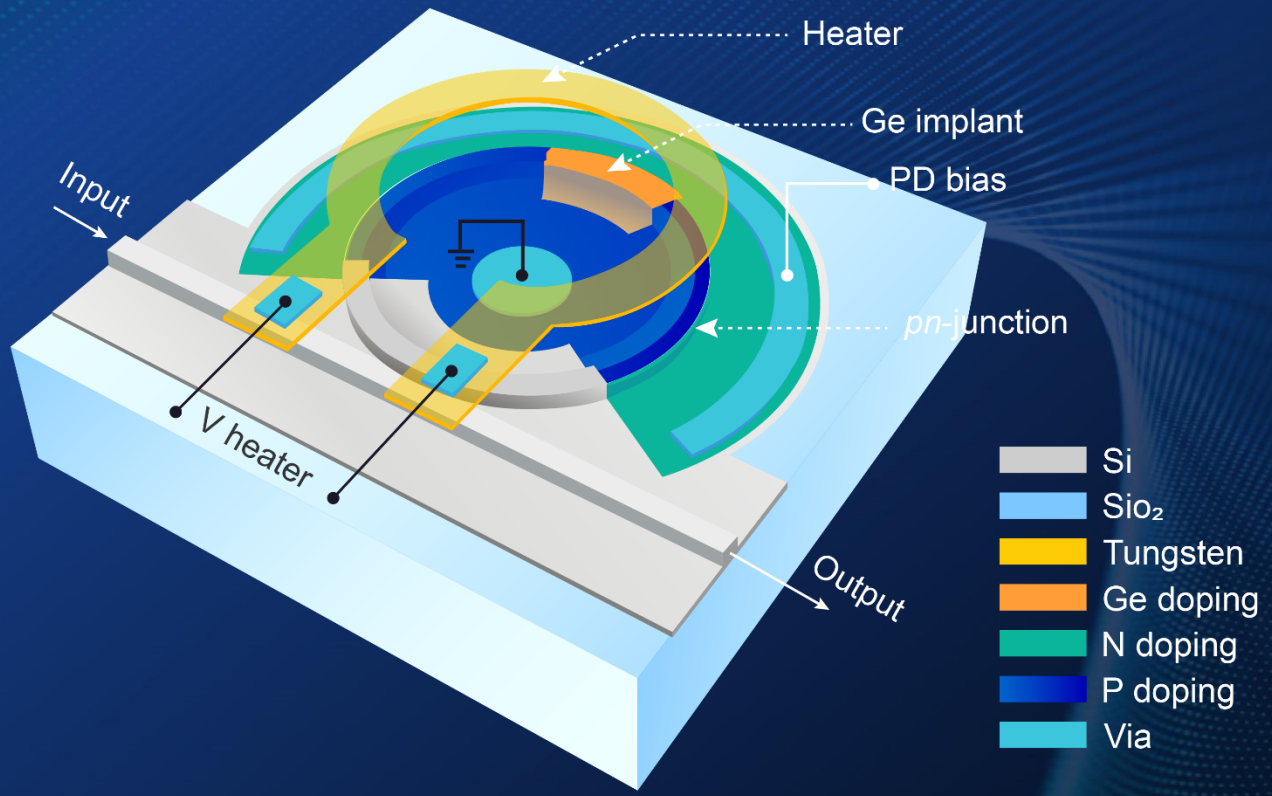
structure	BW (GHz)	V_π (V)	BW/V_π (GHz/V)
segmented drive [11]	67	5	13.4
substrate removed + 35 Ω load [14]	60	7	8.6
low load impedance [12]	47	5.4	8.7
microring-assisted MZMs [13]	67	7.5	8.9
distributed micro-capacitors [1]	61	8.3	7.3
doping optimization [15]	67	5	13.4
conventional [10]	44	8	5.5
conventional [16]	41	7	5.9
slow light waveguide [9]	110	78	1.4
transparent electrodes (This work)	168	7	23
transparent electrodes (This work)	140	5	28

https://doi.org/10.1364/OE.540705

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Modulator selection

2. MRM:



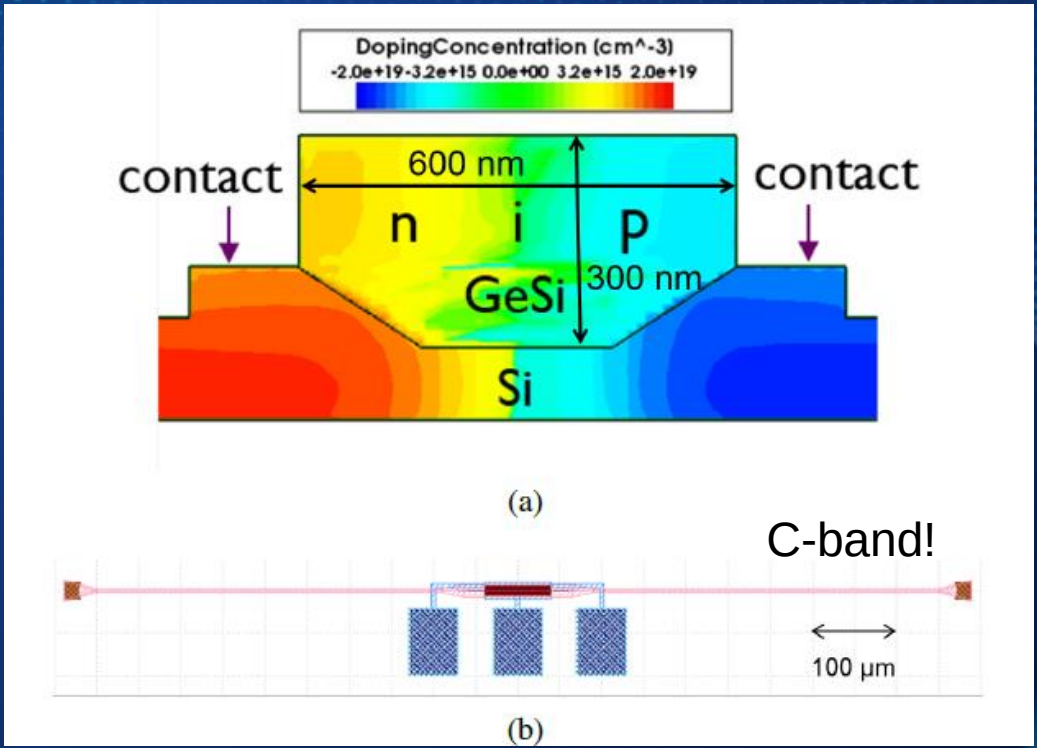
- Small foot print
- Low drive voltage
- High intrinsic electrical bandwidth (due to low resistance)
- Extremely sensitive to temperature
- Demanding on process control
- Trading off extinction ratio against speed
- Not a promising candidate for 400 Gbps/channel and above

Jayatilleka et al., Intel, 2022

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Modulator selection

3. SiGe EAM:



Verbist et al., J. Lightwave Technology, 2016

Feature	SiGe EAM	MZM
Footprint	Very small (~ 50 μm)	Large (millimeters)
Drive Voltage	Low (~ 1V - 3V)	High
Energy Efficiency	High (fJ/bit range)	Moderate
Optical Bandwidth	Narrow (wavelength specific)	Wide (broadband)
Chirp / Dispersion	High (can cause penalty over distance)	Lower than SiGe EAM
Primary Use Cases	Short-reach data centers, AI tensor cores, on-board optical transceivers	Long-haul telecom, coherent optical networks, high-power applications

Courtesy of Gemini

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Modulator selection

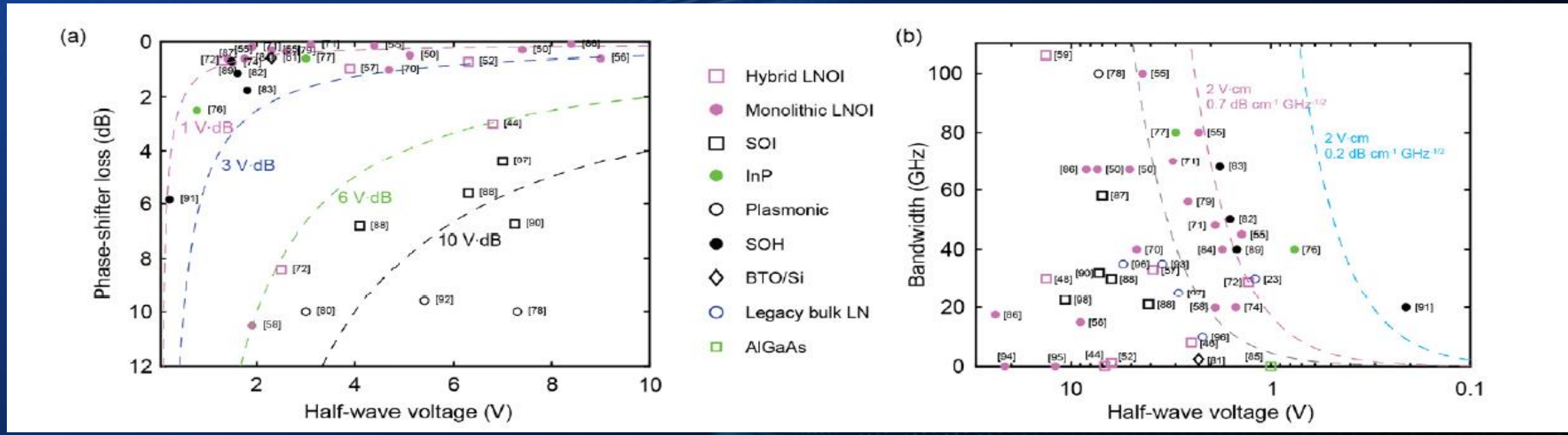
- Other candidates:
  - InP EML (laser+EAM) and MZM
  - Thin-film $LiNbO_3$ (TFLN) MZM
  - Organic
  - Graphene
  - Thin-film $LiTaO_3$
  - …

- InP and TFLN are the two most promising solutions, as these are much more mature than the other contenders.

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TFLN modulators

- UMC Group's TFLN program started on 2021.
  - 6" in mass production, 8" in sampling
- $LiNbO_3$'s excellent optical and E/O properties coupled with mature TFLN substrate infrastructure (up to 8" in substrate size) making TFLN the leading modulator candidate for 400 Gbps/channel and above.

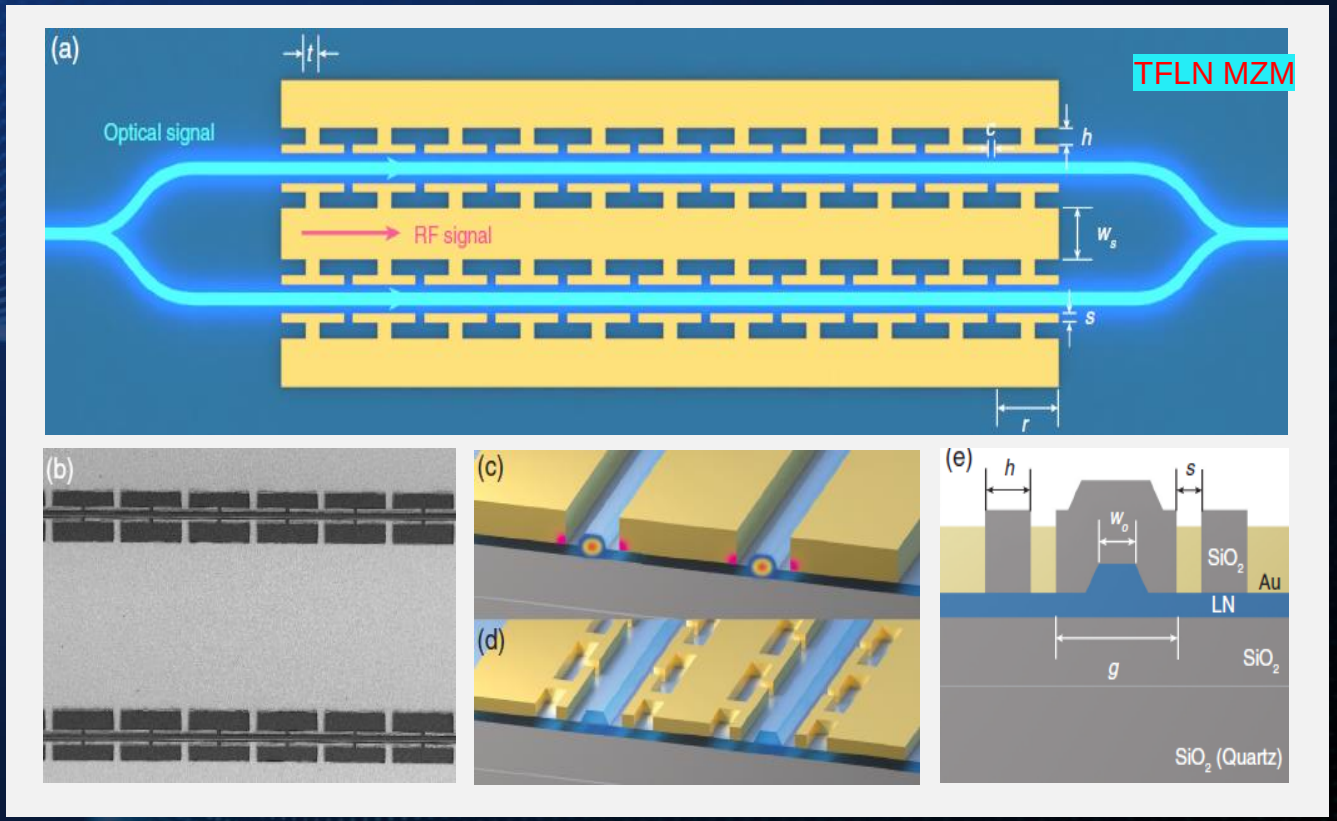


Zhang *et al.*, Optica, 2021

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TFLN pros and cons

- **Strengths:** low loss, high bandwidth (> 110 GHz), good thermal stability, superb linearity.
- **Weaknesses:** large, expensive (compared with Si), integration with SiPh requiring either heterogeneous integration or advanced packaging.



Kharel *et al*., Optica 2021

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TFLN is here to stay

- InP facing severe shortage, adding to TFLN's momentum.
- TFLN the best modulator solution for Coherent Lite given its superb linearity. It is the best solution for 400 Gbps/lane IMDD too.
- Integrating TFLN with PIC is a challenge as well as an opportunity. This is in hot pursuit.
  - Advanced packaging schemes and micro transfer printing are both promising candidates.
  - UMC is developing the integration technology, leveraging our expertise in PIC, TFLN, and advanced packaging.
- Rather diverse applications of TFLN are being explored, across a number of wavelengths. Innovations taking advantage of $LiNbO_3$'s unique optical properties are happening at an unexpected pace. This is perhaps only the tip of the iceberg.

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Ge Photo Diodes

- Good enough for 200 Gbps (bandwidth ~ 50+ GHz) but marginal at 400 Gbps/channel (110+ GHz).
- May still make it to 400 Gbps/channel with process/layout/design optimization.
- High uncertainty whether Ge PD can ever go beyond 400 Gbps.
- InP very expensive and harder to integrate.
- Alternative materials being explored: GeSn, SiSn, etc., but still early on the learning curve.

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Coherent technology comes to the rescue?

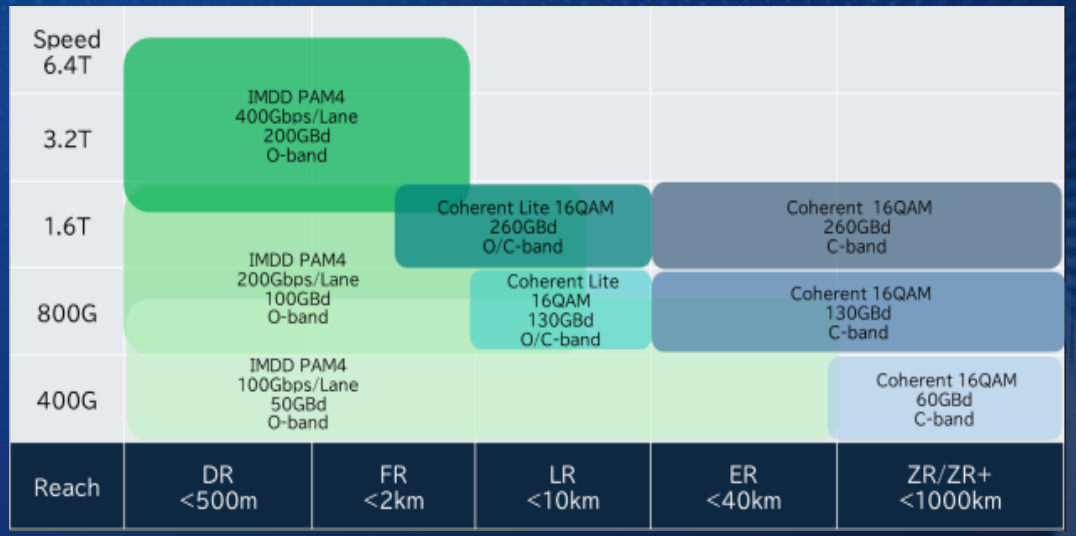
- Traditionally, coherent technology was used for telecom only, not for datacom.
  - Expensive, bulky, and energy hungry.
  - Modulating ***amplitude, phase, and polarization.***
  - Carrying huge data load over very long distances.

- Coherent Lite is now entering datacom as a viable solution for**:**
  - Connecting servers that could be a Km away within the same data center.
  - Providing relief to the bandwidth challenge.
  - Additional optical loss (~ 3 dB) from OCS helps justify Coherent Lite over IM/DD.

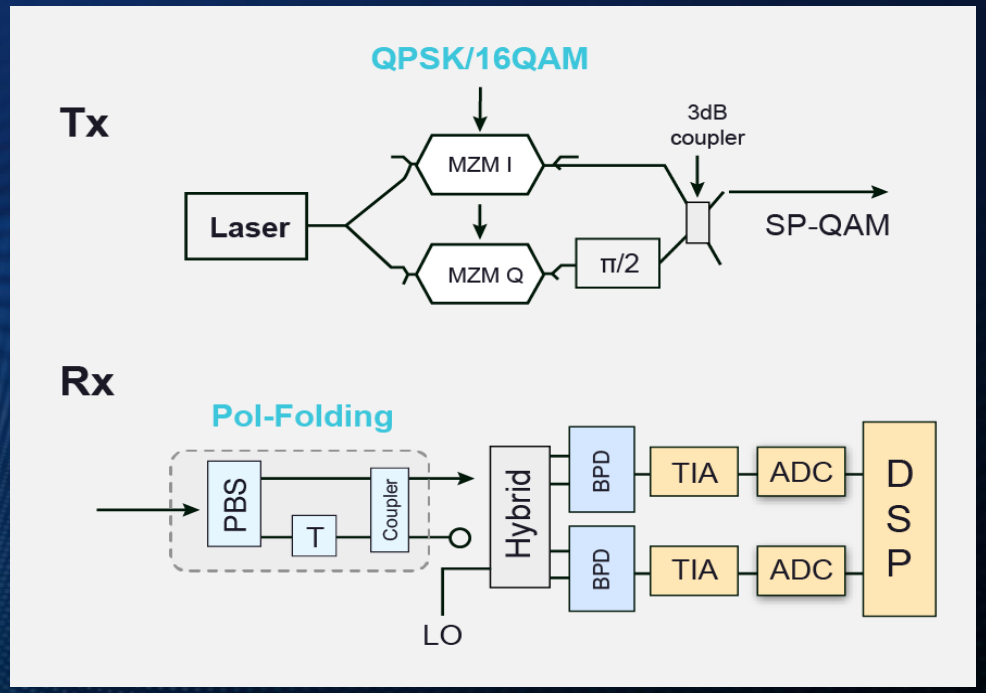
- Coherent Lite could be different from a telecom coherent technology:
  - O-band
  - Shorter reach (2~20 Km)
  - Single polarization
  - Hardware simplified
  - Lower power
  - Lower cost

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Coherent technology comes to the rescue?



https://techtimes.dexerials.jp/en/photonics/coherent-lite-pic/

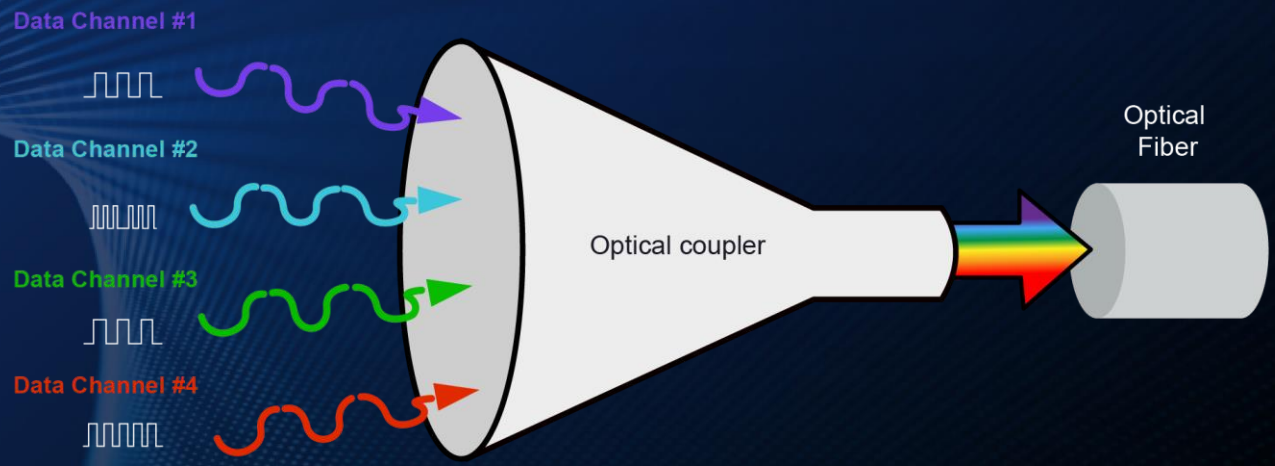


https://fundaai.substack.com/p/deepcoherent-lite-reshapes-ai-optical

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WDM

- Squeezing multiple λ‘s into the same channel.
- DWDM (8 or more λ‘s/fiber) and CWDM (fewer than 8 λ‘s/fiber).
- Actively pursued for scale-up CPO applications to handle the large amount of electronic channels.
- Multiple single- λ lasers are easier to implement but comb-lasers may be a better solution in the long run due to better power efficiency.



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So what is likely to happen at 400 Gbps and beyond, for DCI?

- Adoption of higher-performance modulators (TFLN/InP) and improvement in photo diodes are key factors affecting deployment of plain-vanilla (non-WDM, IM/DD) DCI's with 400 Gbps/channel performance and beyond.
- A combination of WDM, PAM8, and even coherent transmission may be more "elegant" solutions than brute-force bandwidth scaling. And these are being actively pursued.
- The scaling law in DCI's data rate/channel is likely to slow down as transceivers becoming more complicated to enable WDM and coherent coding schemes, and/or to incorporate non-Si (TFLN, InP) modulators.
- As a result, future connectivity scaling will increasingly rely on heterogeneous integration and advanced photonic platforms, rather than brute-forcing wider bandwidth from each component.

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Conclusion

- Winning solutions for future DCI need to be balanced in cost and performance, likely leveraging optical components made by different materials and integrated together seamlessly through advanced packaging schemes.

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Thank you!

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