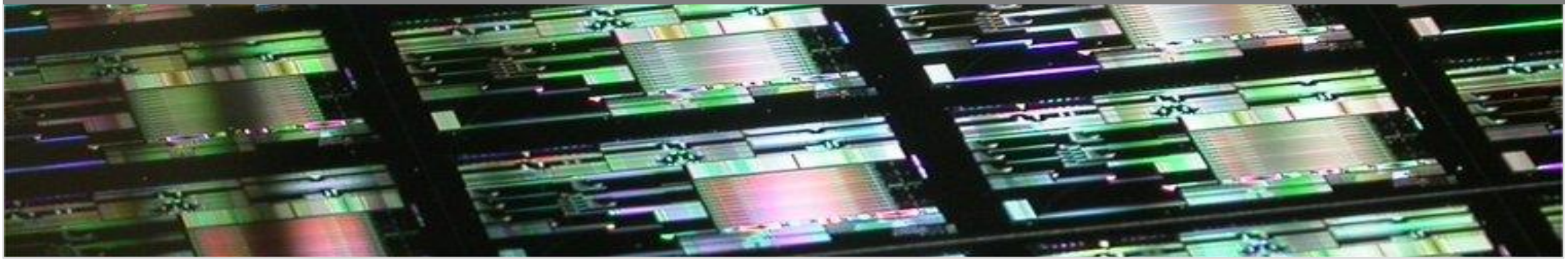
Licht als Schlüssel zur Effizienz – Photonische Technologien für die Kommunikation in KI-Systemen

Christian Koos

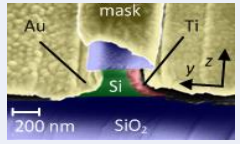
Institute of Photonics and Quantum Electronics (IPQ), Karlsruhe Institute of Technology (KIT), 76131 Karlsruhe, Germany
Institute of Microstructure Technology (IMT), Karlsruhe Institute of Technology (KIT), 76344 Eggenstein-Leopoldshafen, Germany
christian.koos@kit.edu



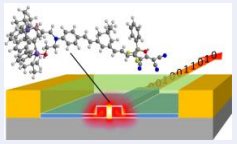
Institute of Photonics und Quantum Electronics (IPQ) & Institute for Microstructure Technology (IMT): Research Topics

Karlsruhe Institute of Technology

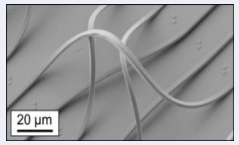
Photonic and Plasmonic Devices



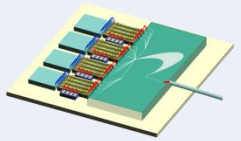
Hybrid Photonic Integrated Circuits



Additive 3D Nanofabrication



Photonic-Electron. Packaging and Mechanics



Algorithms and Digital Signal Processing

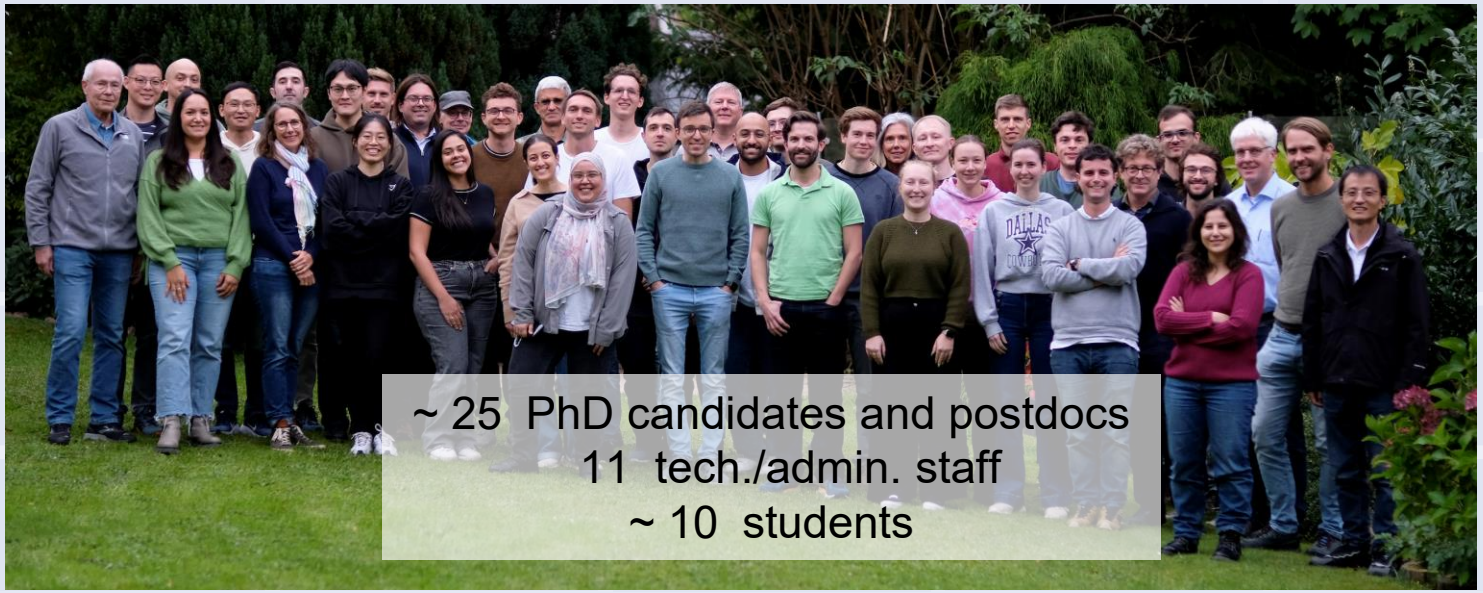


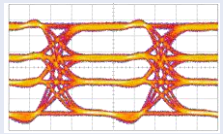

C. Koos


S. Randel


W. Freude


T. Huber-Loyola

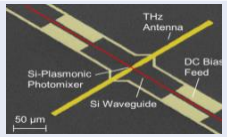




Optical and THz Communications



Optical Metrology and Sensing



Teratronic Signal Processing



Quantum Electro-Optics

Technology transfer:

vanguard AUTOMATION MYCRONIC
www.vanguard-automation.com

SiLOriX efficient connections
www.silorix.com

DEEPLIGHT™
www.deeplight.ai

LXT
www.luxtelligence.ai

Keystone photonics
www.keystone-photonics.com

Teragear
www.teragear.ai

Karlsruhe Center of Optics and Photonics (KCOP)



- Overall mission: Establishing an internationally outstanding nanofabrication center, geared towards research, education, and innovation in Optics & Photonics and Quantum Technologies
- Investment approx. 56 M€ (~ 36 M€ building, ~ 20 M€ equipment)

(HGF strategic expansion investment, “Strategische Ausbauinvestitionen”)

4370 m² total area

1950 m² cleanroom area (ISO class 5 – 7 + grey room)

320 m² laboratory

270 m² office

Since 2012	June 2017	June 2018	Jan 2018 –Dec 2022	Jan 2023 – April 2026	July 2026 – October 2026	As of October 2026
Internal discussion	Proposal submitted	Funding decision	Planning	Construction	Installation of equipment	Operation

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www.keystone-photonics.com

www.deeplight.ai

www.teragear.ai

Summary

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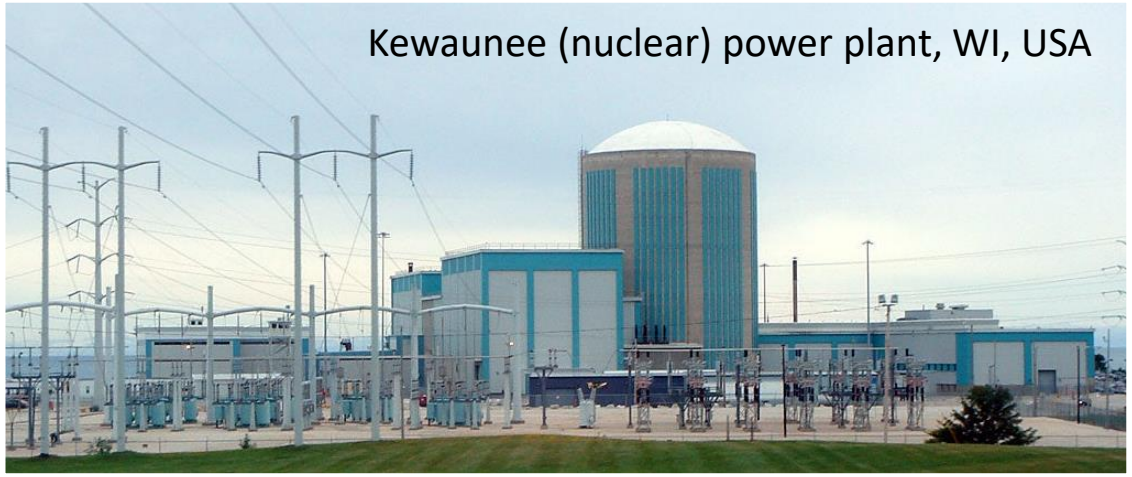
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Summary

Supercomputers for AI training



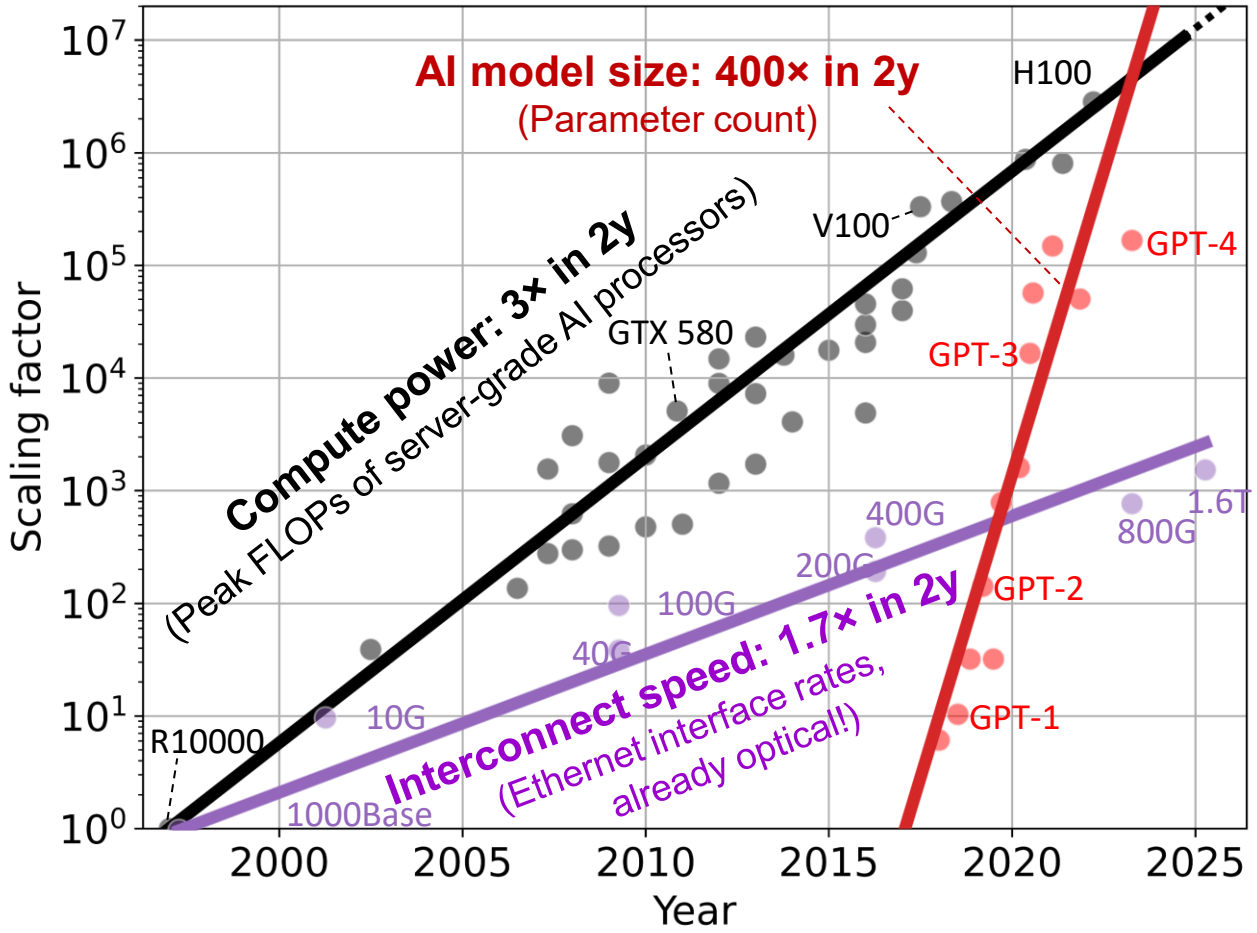


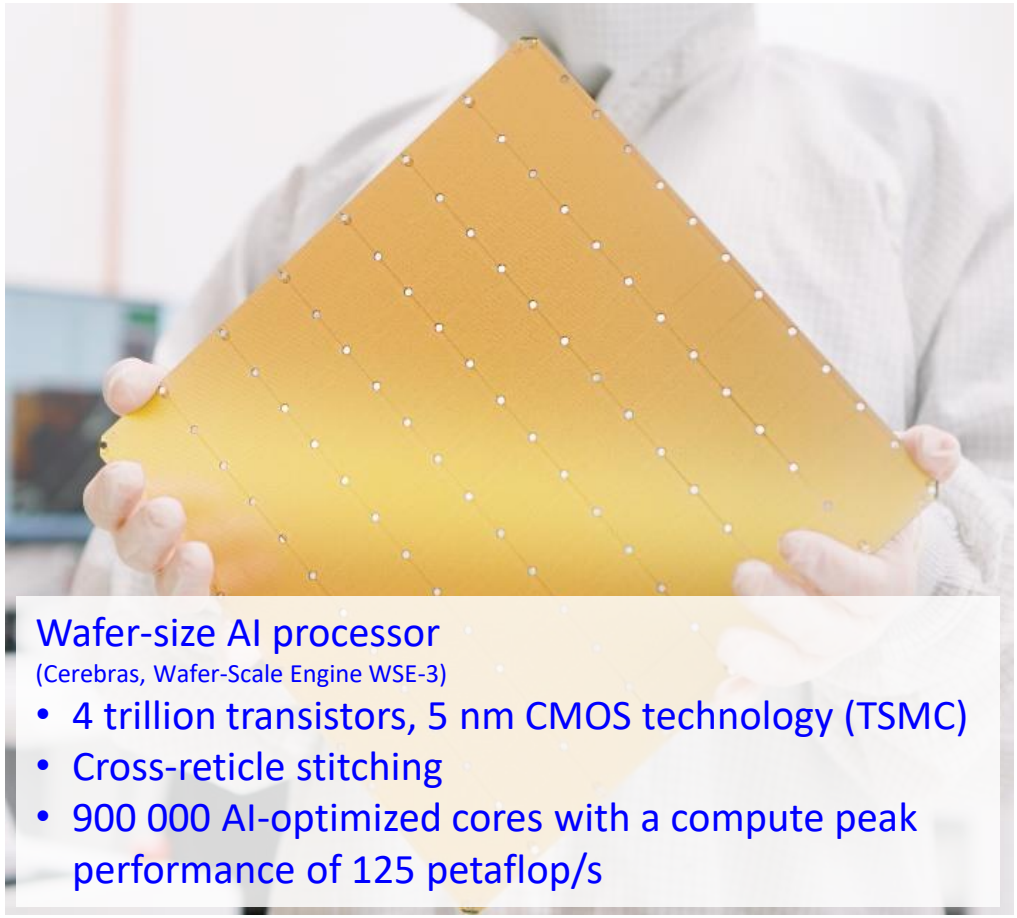
- Training of large language models (LLM) with 10^{11} … 10^{12} parameters
- „Hundreds of thousands of GPUs“
  (NVIDIA B200 and B300, Blackwell architecture)
- Approx. 200 000 km optical fibers
- Estimated compute power > 20 EFlop/s
  (“ten times faster than the leading supercomputers today”)
- Power consumption: > 1 GW
  (probably around 3 GW)

Image sources: Wikipedia, Microsoft

Artificial-intelligence (AI) and bandwidth demand

- Growth of AI models is current outpacing any known scaling laws in information and communication technology (ICT)
- Interconnect bottleneck as the main scalability challenge
- Needs disruptive innovations on all levels, in particular photonics with unprecedented density and efficiency

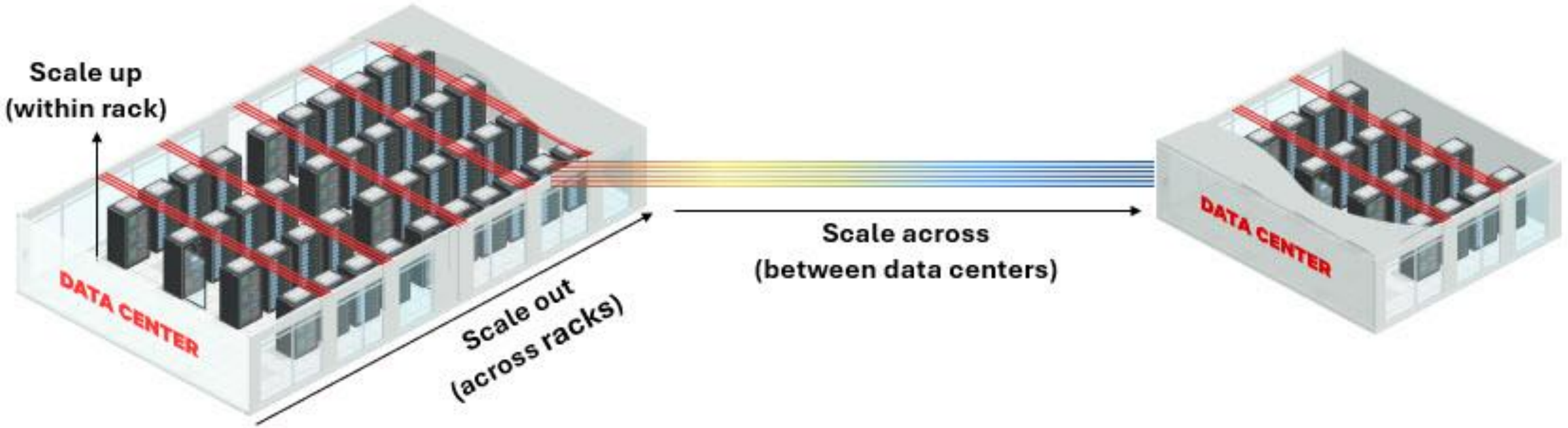




Wafer-size AI processor
(Cerebras, Wafer-Scale Engine WSE-3)

- 4 trillion transistors, 5 nm CMOS technology (TSMC)
- Cross-reticle stitching
- 900 000 AI-optimized cores with a compute peak performance of 125 petaflop/s

Scaling AI data centers up, out, and across…

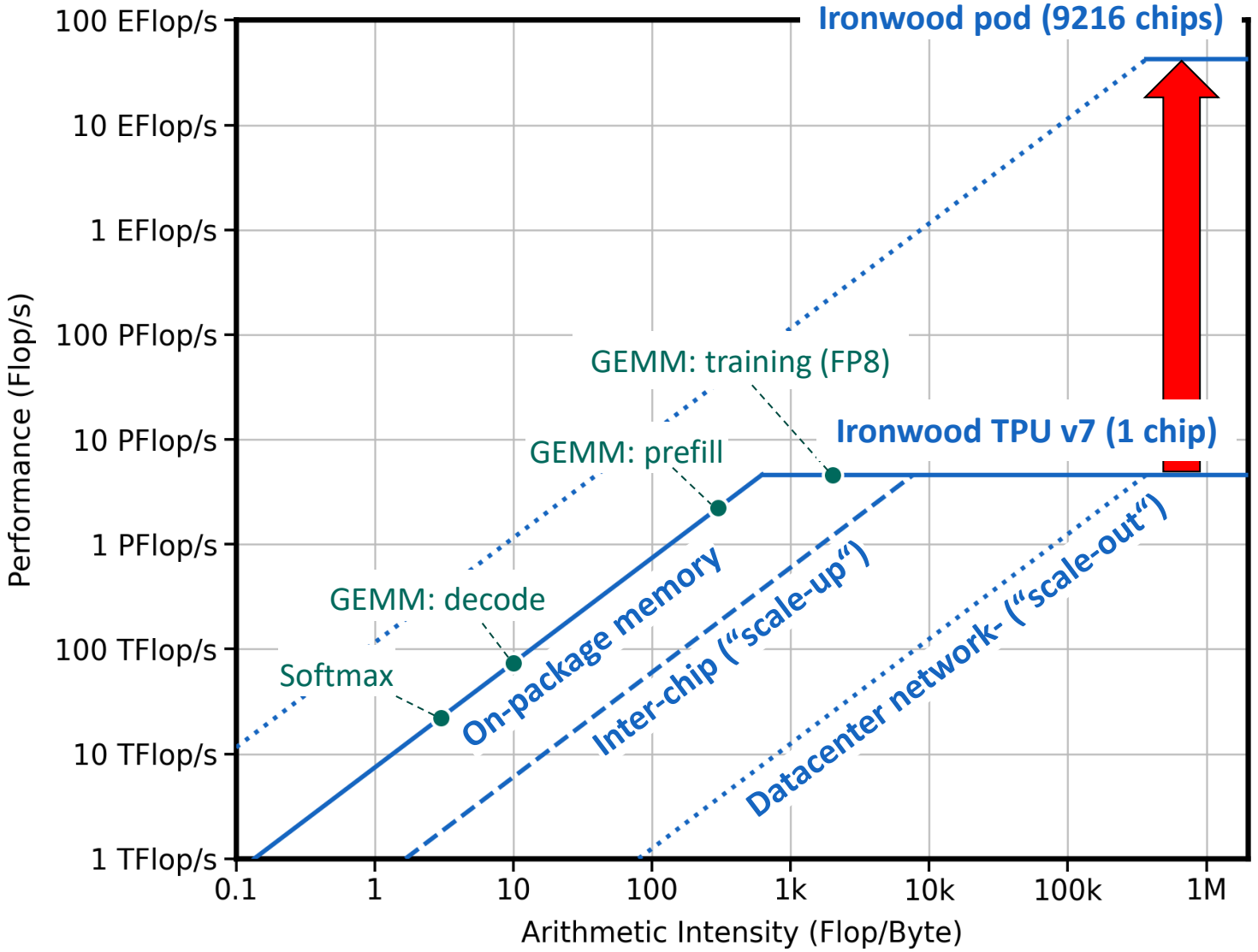


- Scale-up: Connecting GPUs within local compute clusters (racks; typically 72 GPUs, up to approx. 300 PFlop/s)
  → Copper cables (so far)
- Scale-out: Connecting clusters across racks
  → Fibers (intensity modulation and direct detection, IM/DD)
- Scale-across: Connecting entire data centers into AI “factories” that span sites
  → Fibers (coherent transmission and wavelength-division multiplexing, WDM)

Integrated Photonics

Adapted from https://www.ciena.com/

The Roofline Model: How much I/O bandwidth does AI need?



- Key to efficient computing: Matching the bandwidth-to-compute ratio of the hardware to the arithmetic intensity of the underlying workload
- Example: Ironwood TOU v7 (AI chip by Google)
  - Peak compute performance: 4.6 PFlop/s
  - Memory bandwidth (HBM, unidir.): 7.4 TB/s
    → Already I/O limited for a wide range of AI tasks!
  - Inter-chip interconnects (ICI, unidir.): 0.6 TB/s ("Scale-up") → Almost always I/O limited!
  - Datacenter network (unidir.): 12.5 GB/s ("Scale-out") → Hopelessly I/O limited!

⇒ AI clusters could use orders of magnitude more I/O bandwidth in the scale-out (scale-up) domain!
⇒ Needed: Optical links with radically improved scalability and (energy) efficiency!

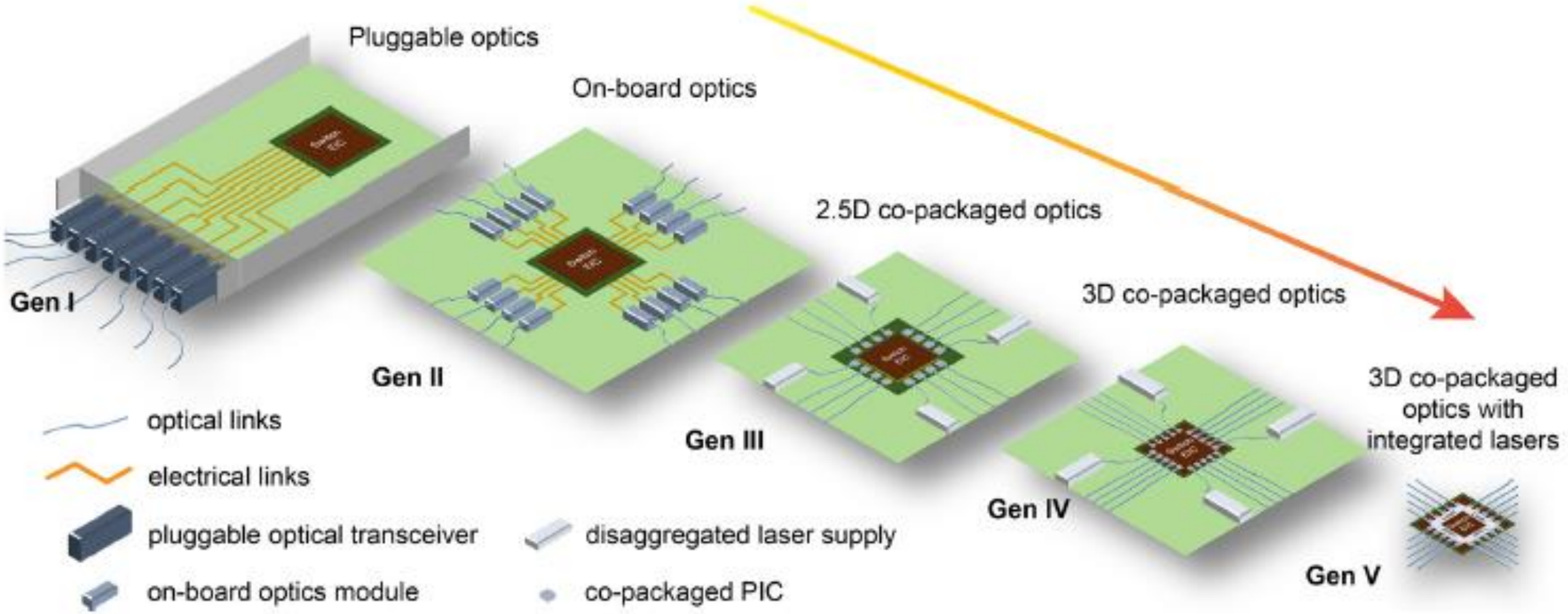
Very hungry
Simple calculations

How data-hungry is your algorithm?

Not so hungry
Complex calculations

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IPQ

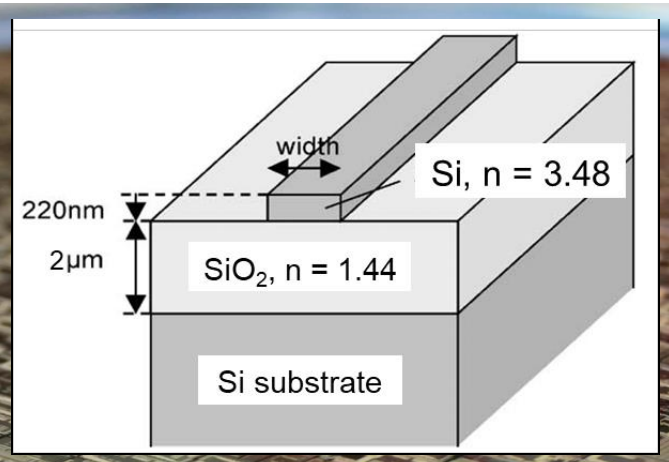
Evolution of optical transceivers: From pluggable to co-packaged optics (CPO)



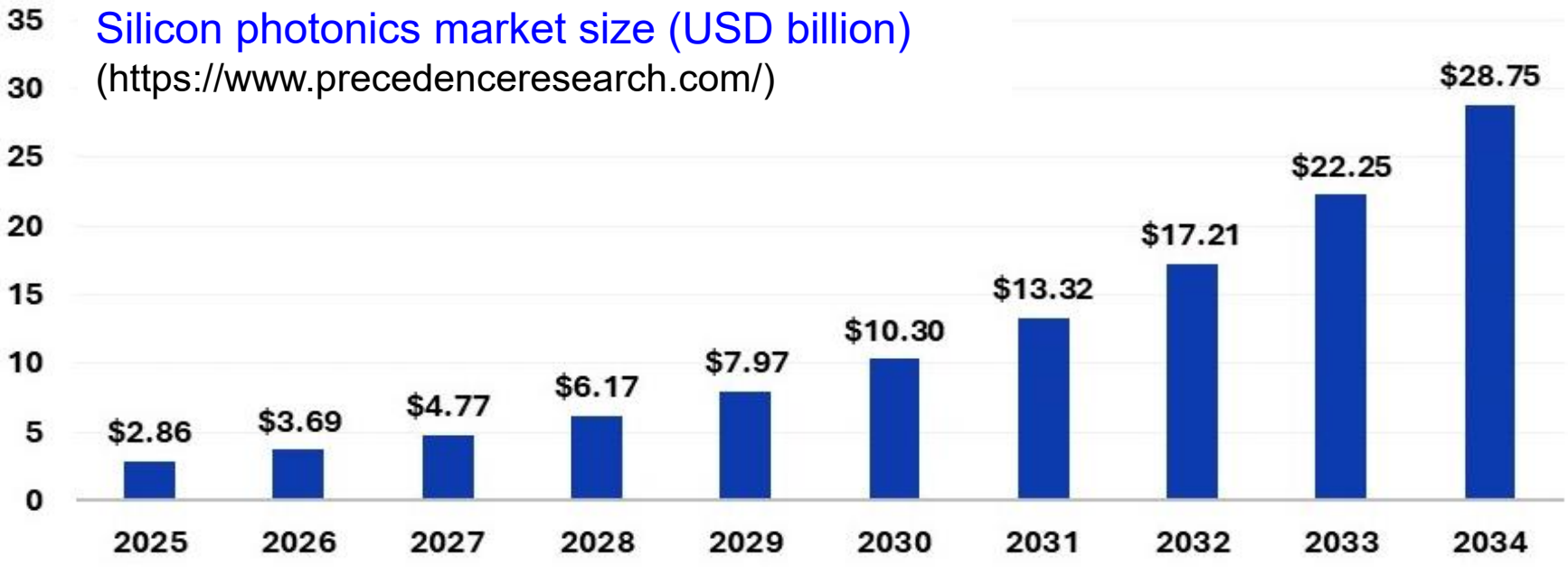
Margalit *et al.*, Appl. Phys. Lett. **118**, 220501-1 – 220501-4 (2021)

Technology push: Silicon photonics

- High-index-contrast Si-on-insulator (SOI) waveguides
  ⇒ High integration density
- Mature CMOS technology
  ⇒ Large-scale photonic-electronic integration with high yield
- Ecosystem of foundries
  ⇒ Fabless fabrication: Shared investment and development costs, process design kits (PDK)



Silicon photonic wafer
∅ = 200 mm – 300 mm
Approx. 100 000 devices



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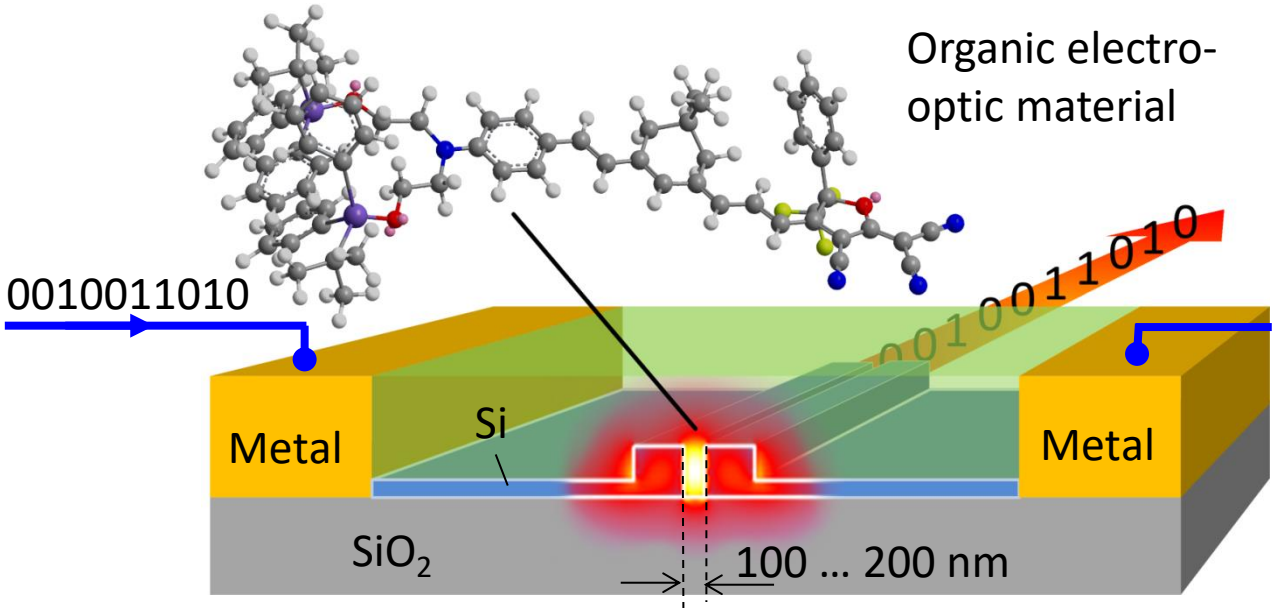
www.keystone-photonics.com

www.deeplight.ai

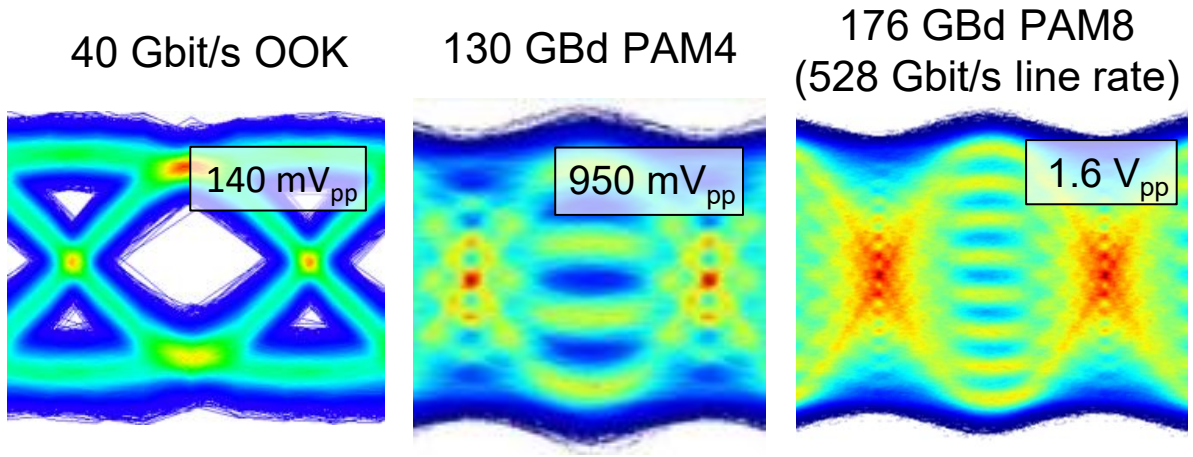
www.teragear.ai

Summary

Silicon-organic hybrid (SOH) electro-optic modulators



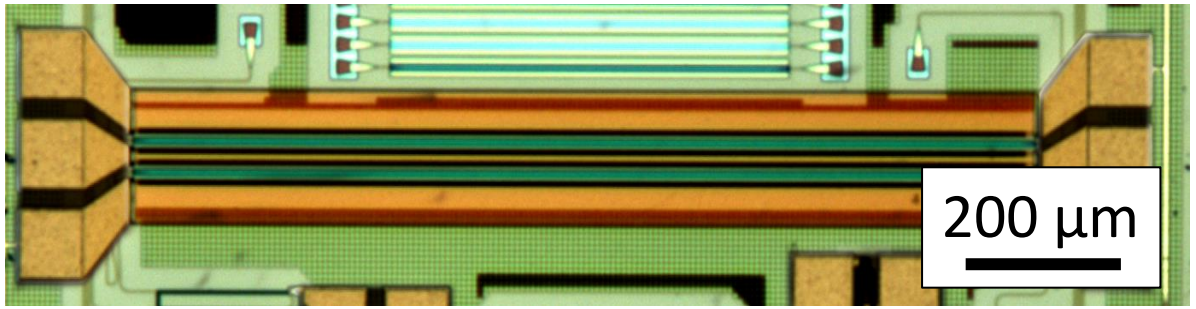
SilOriX GmbH



Concept: Combine silicon-on-insulator waveguides with organic electro-optic cladding material

- Highly efficient: r_{33} = 390 pm/V, $U_\pi L \approx$ 0.3 Vmm
- Efficient low-voltage operation: < 200 mV_{pp} for MZM
- Back-end-of-line integration into standard silicon photonics (SiPh)

⇒ Intrinsic scalability and compatibility with the SiPh device portfolio

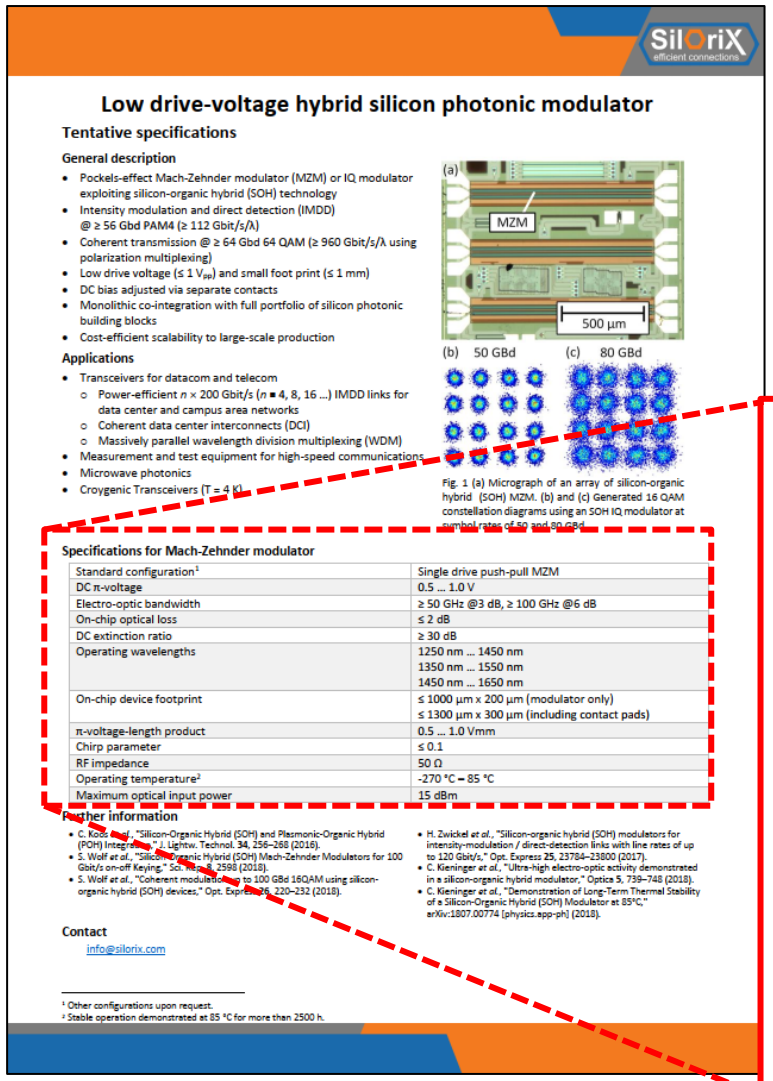


Kieninger *et al.*, Optica **5**, 739 - 748 (2018)
Freude *et al.*, IEEE J. Sel. Top. Quant. Elec.. **30**, 3400222 (2024)

Eschenbaum *et al.*, ECOC 2022, paper Th3B.3, (post-deadline paper)
Schwarzenberger *et al.*, OFC 2025, paper M4K.1

Technology transfer: Tentative data sheet

www.silorix.com



Low drive-voltage hybrid silicon photonic modulator

Tentative specifications

General description

- Pockels-effect Mach-Zehnder modulator (MZM) or IQ modulator exploiting silicon-organic hybrid (SOH) technology
- Intensity modulation and direct detection (IMDD) @ ≥ 56 Gbd PAM4 (≥ 112 Gbit/s/λ)
- Coherent transmission @ ≥ 64 Gbd 64 QAM (≥ 960 Gbit/s/λ using polarization multiplexing)
- Low drive voltage (≤ 1 V_{pp}) and small foot print (≤ 1 mm)
- DC bias adjusted via separate contacts
- Monolithic co-integration with full portfolio of silicon photonic building blocks
- Cost-efficient scalability to large-scale production

Applications

- Transceivers for datacom and telecom
  - Power-efficient n x 200 Gbit/s (n = 4, 8, 16 …) IMDD links for data center and campus area networks
  - Coherent data center interconnects (DCI)
  - Massively parallel wavelength division multiplexing (WDM)
- Measurement and test equipment for high-speed communications
- Microwave photonics
- Croygenic Transceivers (T = 4 K)

(a) MZM 500 µm (b) 50 GBd (c) 80 GBd

Fig. 1 (a) Micrograph of an array of silicon-organic hybrid (SOH) MZM. (b) and (c) Generated 16 QAM constellation diagrams using an SOH IQ modulator at symbol rates of 50 and 80 GBd.

Specifications for Mach-Zehnder modulator

Standard configuration[1]	Single drive push-pull MZM
DC π-voltage	0.5 … 1.0 V
Electro-optic bandwidth	≥ 50 GHz @3 dB, ≥ 100 GHz @6 dB
On-chip optical loss	≤ 2 dB
DC extinction ratio	≥ 30 dB
Operating wavelengths	1250 nm … 1450 nm 1350 nm … 1550 nm 1450 nm … 1650 nm
On-chip device footprint	≤ 1000 µm x 200 µm (modulator only) ≤ 1300 µm x 300 µm (including contact pads)
π-voltage-length product	0.5 … 1.0 Vmm
Chirp parameter	≤ 0.1
RF impedance	50 Ω
Operating temperature[2]	-270 °C – 85 °C
Maximum optical input power	15 dBm

Further information

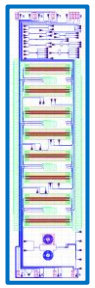
- C. Koos et al., "Silicon-Organic Hybrid (SOH) and Plasmonic-Organic Hybrid (POH) Integration," J. Lightw. Technol. 34, 256–268 (2016).
- S. Wolf et al., "Silicon-Organic Hybrid (SOH) Mach-Zehnder Modulators for 100 Gbit/s on-off Keying," Sci. Rep. 8, 2598 (2018).
- S. Wolf et al., "Coherent modulation up to 100 GBd 16QAM using silicon-organic hybrid (SOH) devices," Opt. Express 26, 220–232 (2018).
- H. Zwickel et al., "Silicon-organic hybrid (SOH) modulators for intensity-modulation / direct-detection links with line rates of up to 120 Gbit/s," Opt. Express 25, 23784–23800 (2017).
- C. Kieninger et al., "Ultra-high electro-optic activity demonstrated in a silicon-organic hybrid modulator," Optica 5, 739–748 (2018).
- C. Kieninger et al., "Demonstration of Long-Term Thermal Stability of a Silicon-Organic Hybrid (SOH) Modulator at 85°C," arXiv:1807.00774 [physics.app-ph] (2018).

Contact

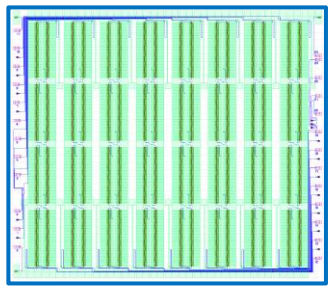
info@silorix.com

[1] Other configurations upon request.
[2] Stable operation demonstrated at 85 °C for more than 2500 h.

8 x SOH



8 x pn-type SiP



1 mm

Long-term thermal and photochemical stability

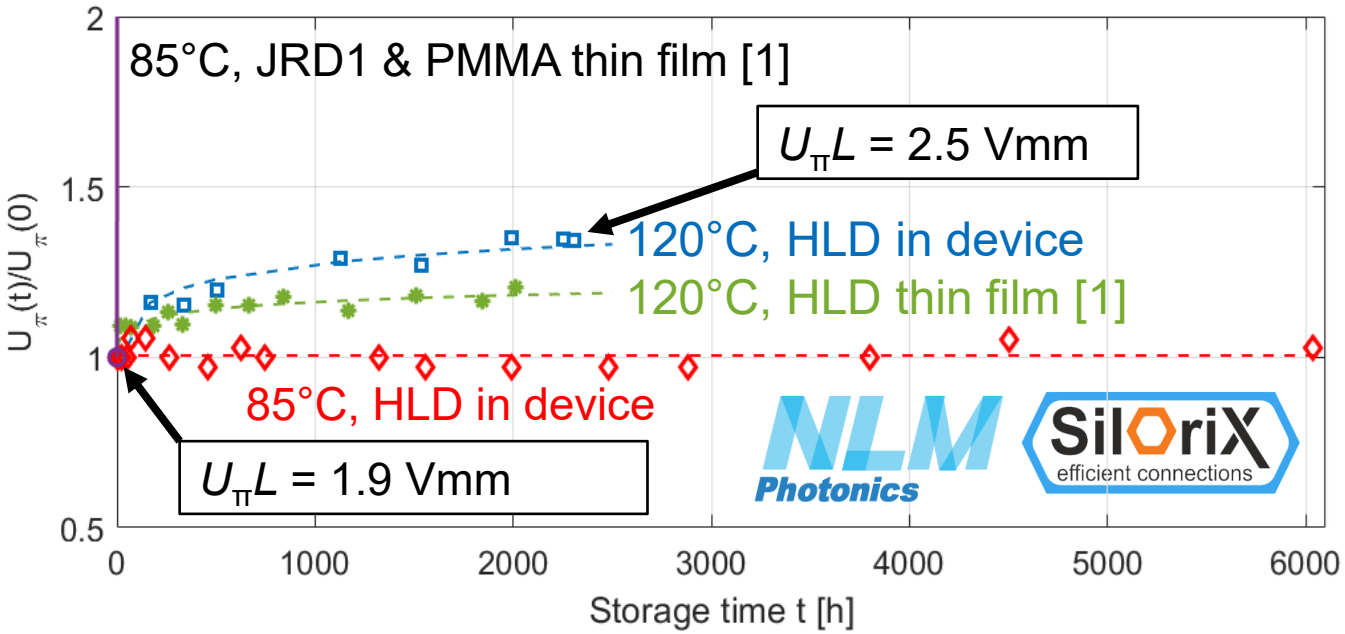
Thermal stability
Conservation of acentric chromophore alignment

Approach 1: Stabilization through a matrix with high glass-transition temperature T_g

Eschenbaum *et al.,* ECOC 2022, paper Th3B.2 (post-deadline paper)
Kieninger *et al.,* Opt. Express **26**, 27955-27964 (2018)

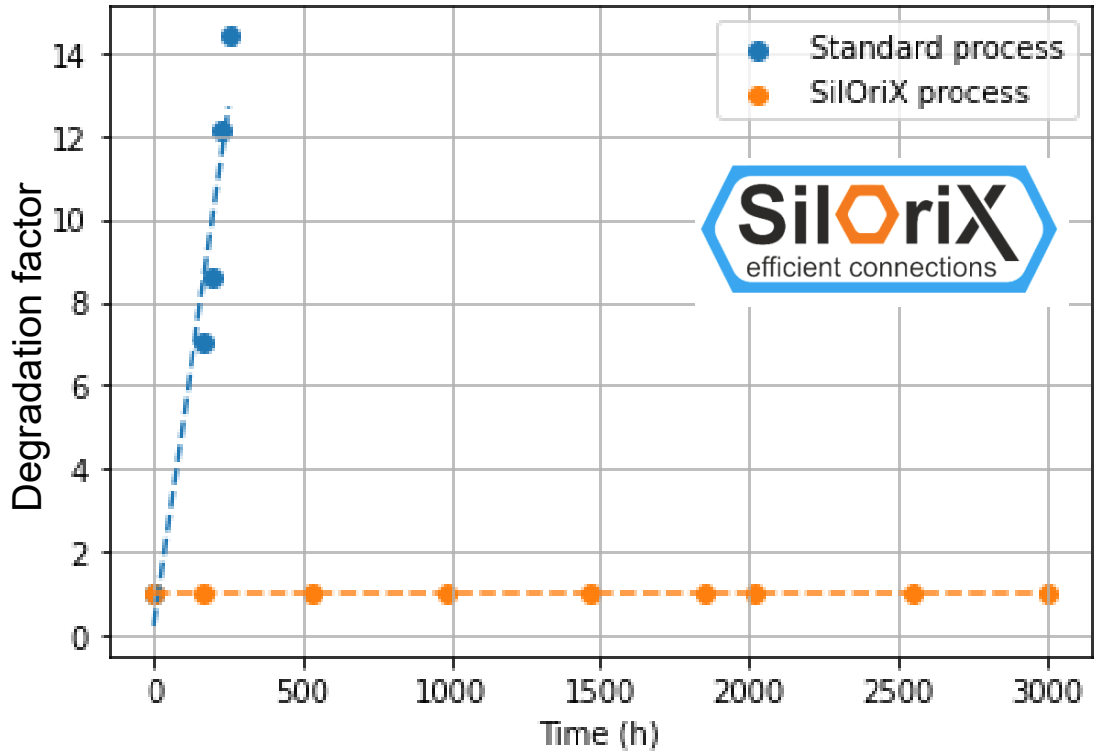
Approach 2: Cross-linking of electro-optic chromophores after poling

Schwarzenberger *et al.,* ECOC 2023, paper We.A.4.2



Photochemical stability
Chip-level encapsulation

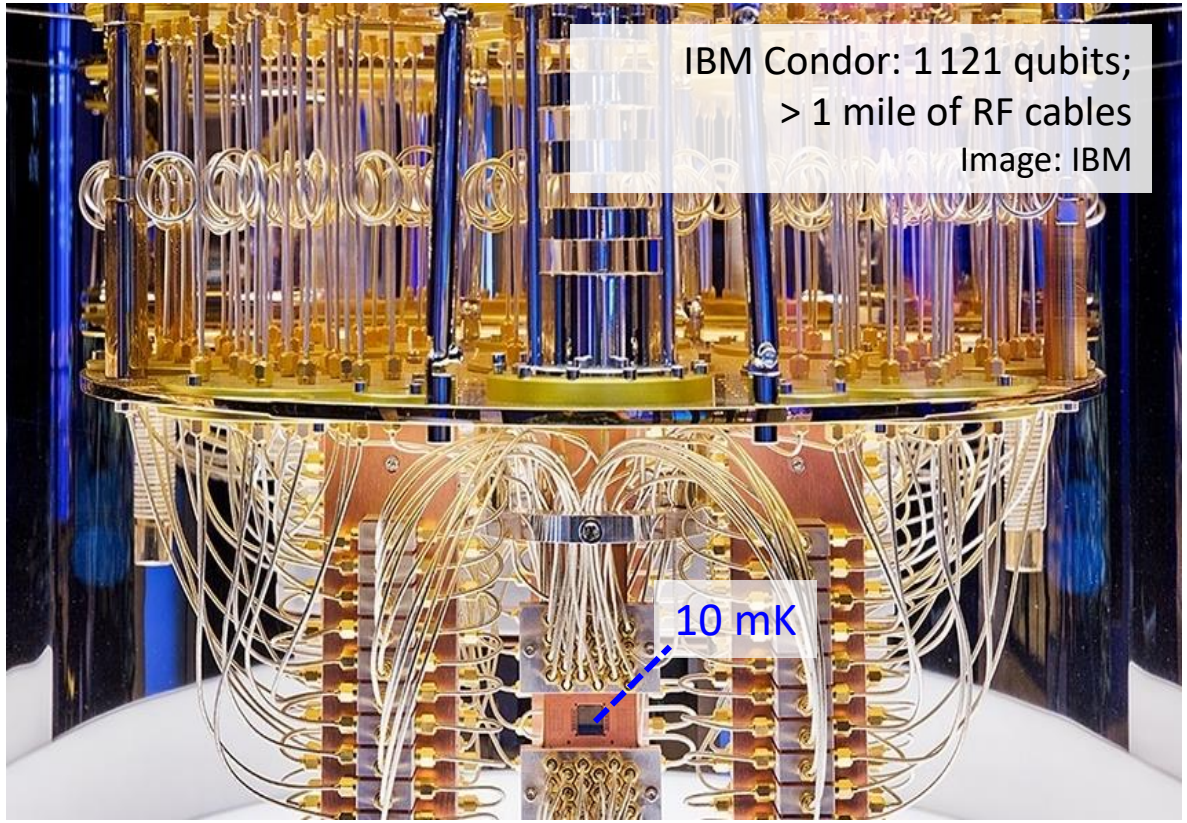
Photo-degradation @ 10 dBm in an on-chip slot waveguide (5 MW/cm²)



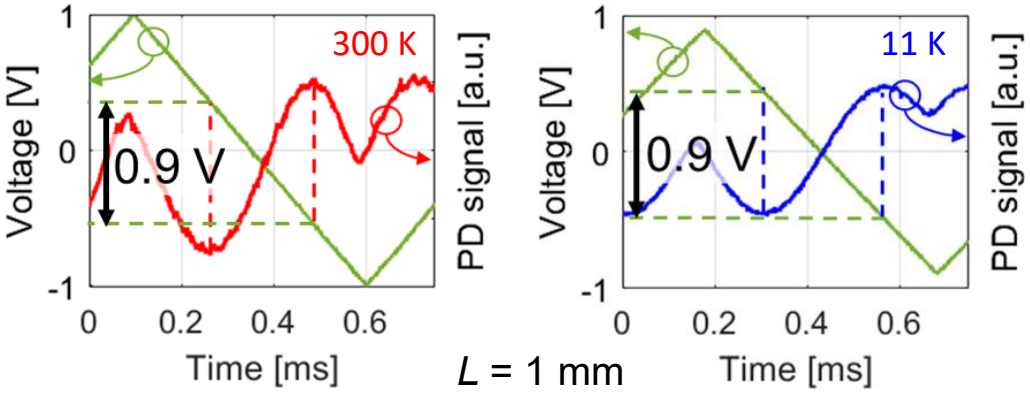
Mertens *et al.,* PIC Magazine **3,** 18-23 (2024)

Cryogenic transceivers: Optical read-out of quantum systems

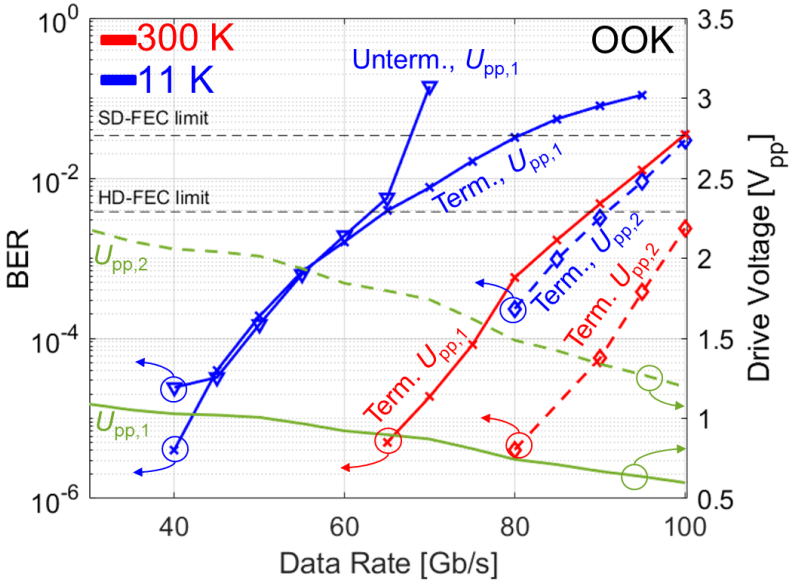
- Optical egress links: Connecting cryogenic processors (quantum processors, RSFQ logic) to the outside world
- Key: Energy-efficient EO modulators for cryogenic operation



Low π-voltage of SOH MZM conserved at cryogenic temperatures:



➔ First MZM with sub-1V U_π at cryogenic temperatures



Schwarzenberger *et al.*, CLEO 2023, Paper STh5C (post-deadline paper)

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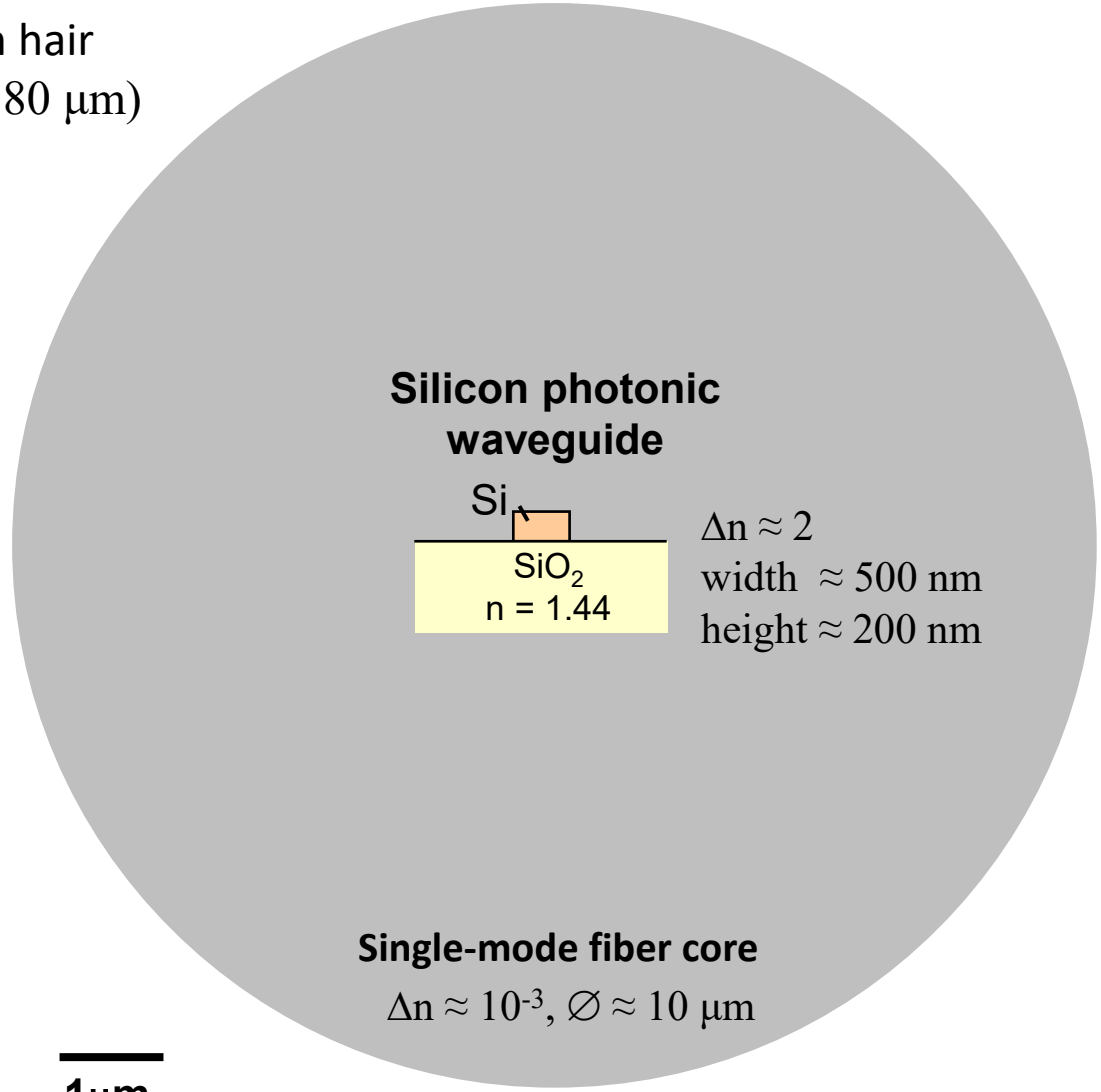
www.keystone-photonics.com

www.deeplight.ai

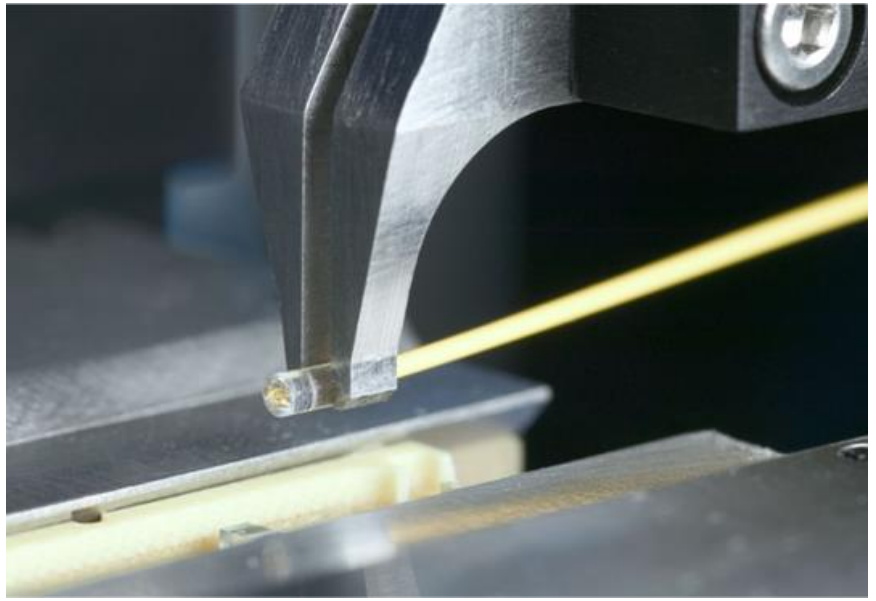
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Summary

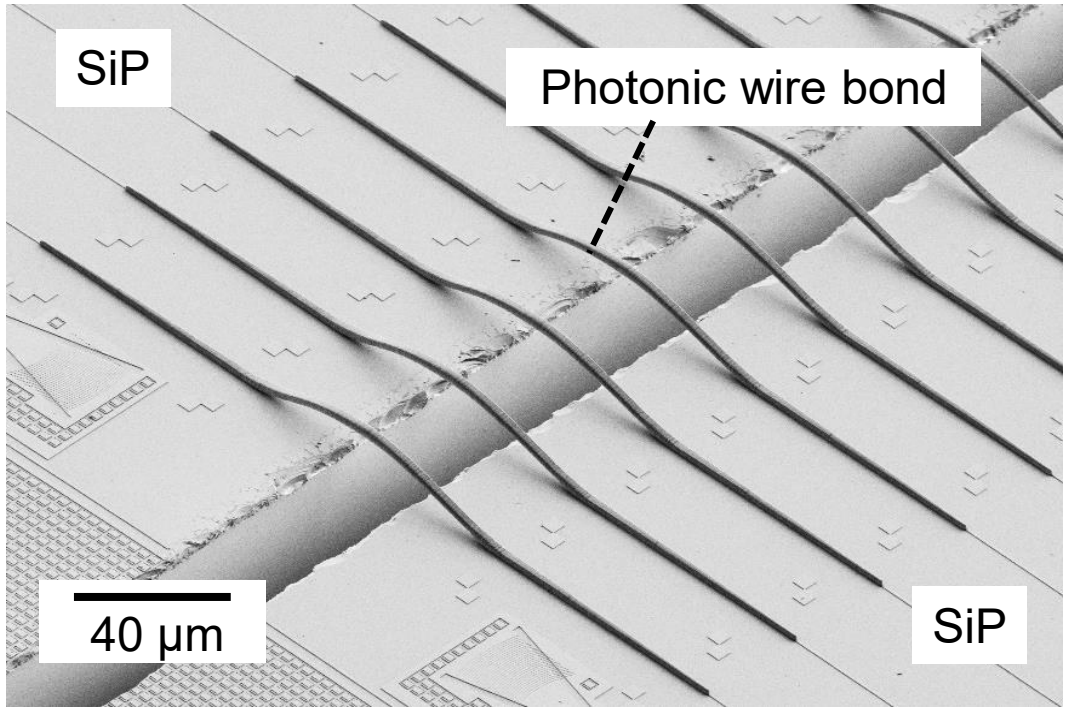
Packaging and assembly challenges in photonics



- Mode matching: Additional micro-optical elements
- (Active) alignment: Slow, expensive, not scalable



Photonic wire bonds: 3D-printed chip-chip connections

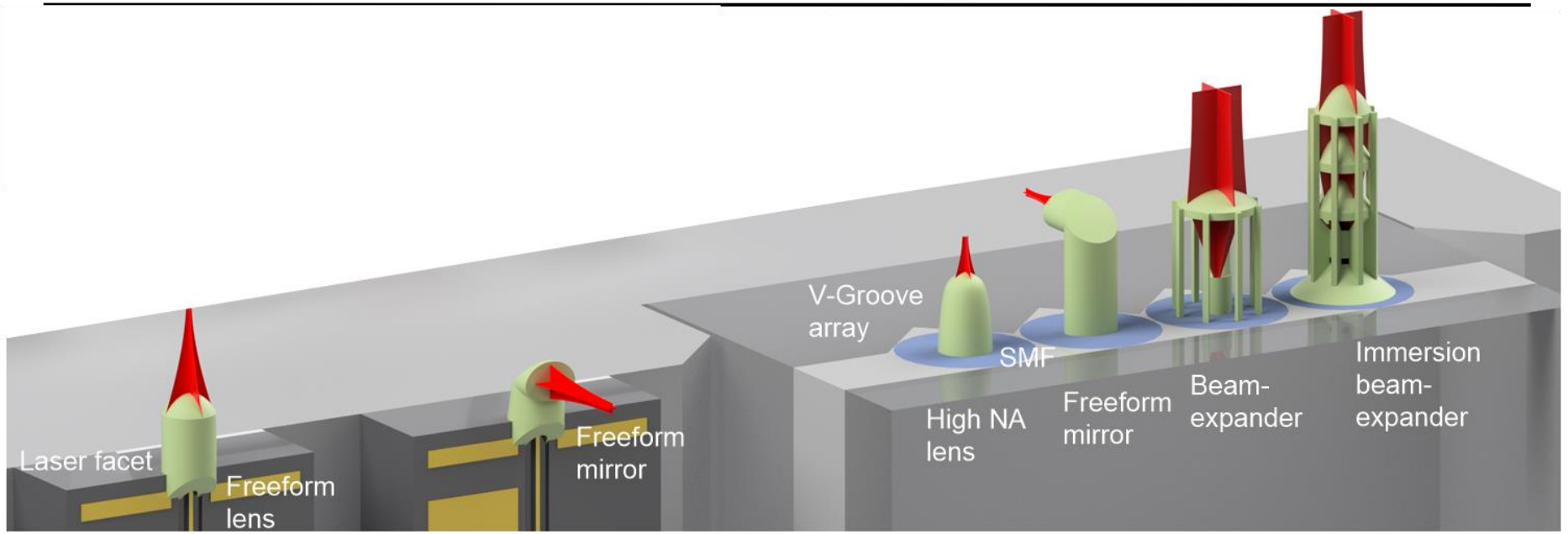


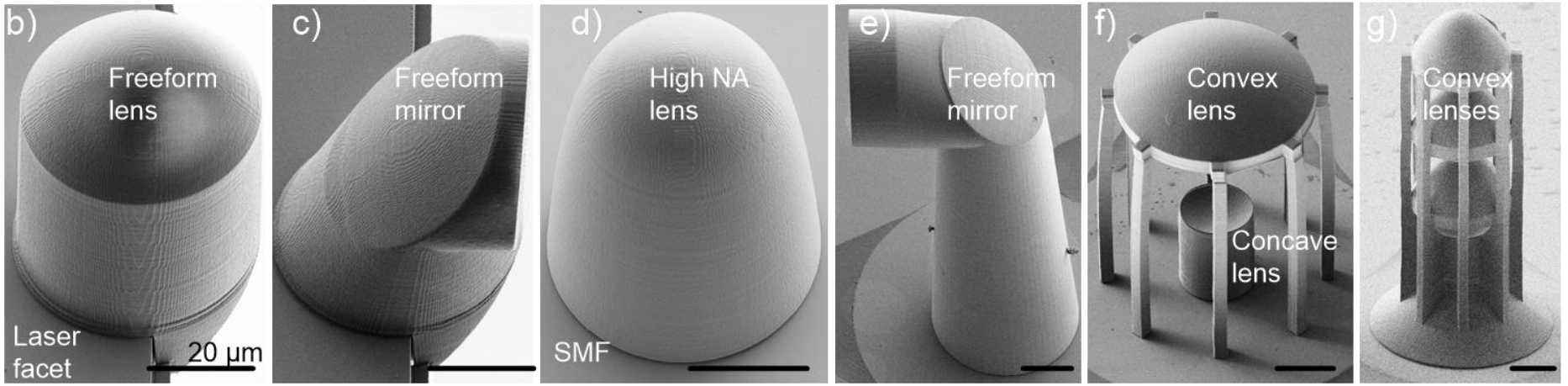
In-situ fabrication of waveguides by multi-photon lithography:

- No high-precision/active alignment required
- Highly scalable automated fabrication
- Can connect to arbitrary mode fields
- High interconnect density

Billah *et al.*, Optica **5**, 876-883 (2018)
Blaicher *et al.*, Light: Science and Applications **9**, 72 (2020)

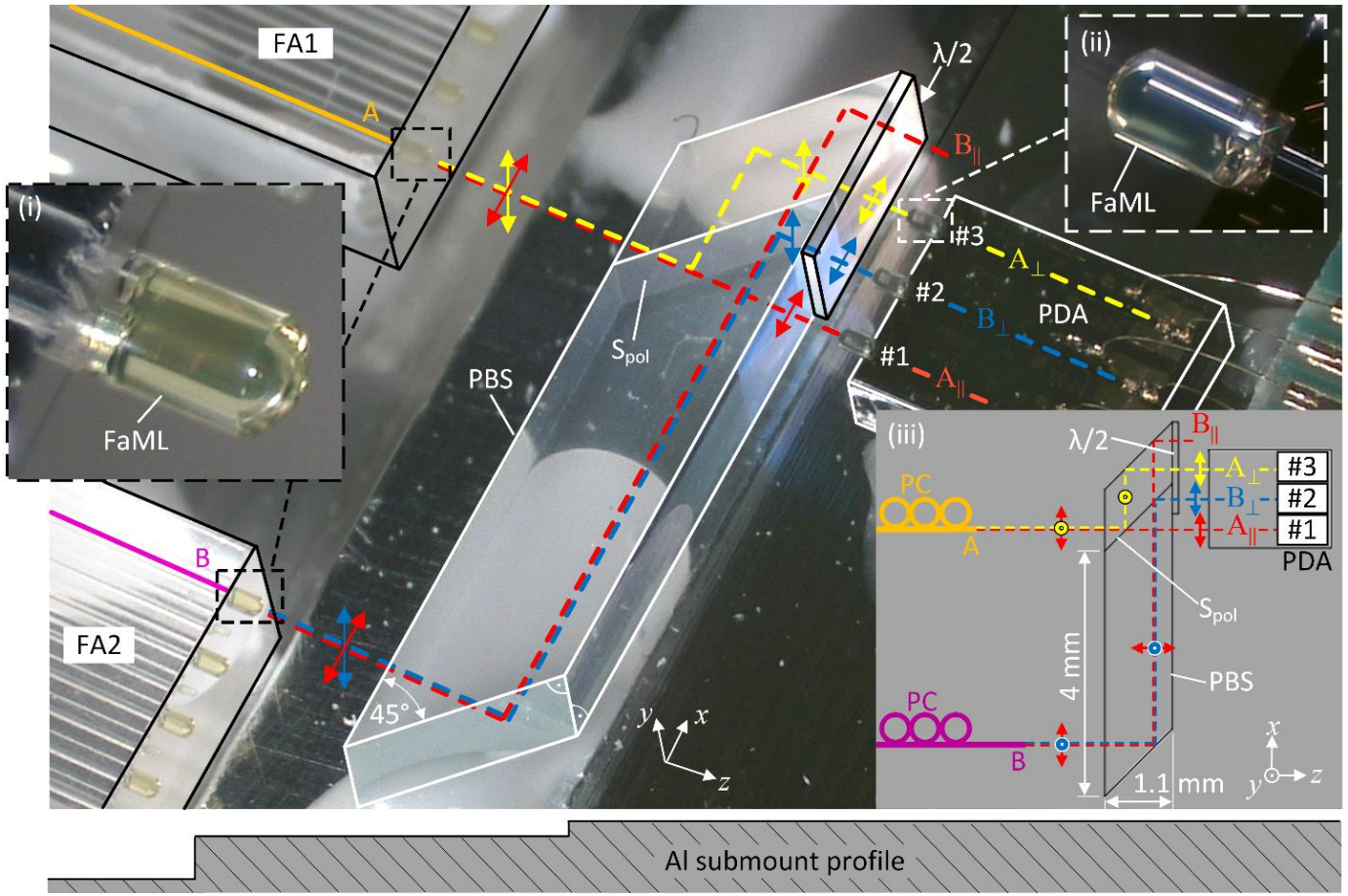
Facet-attached micro-lenses (FaML)

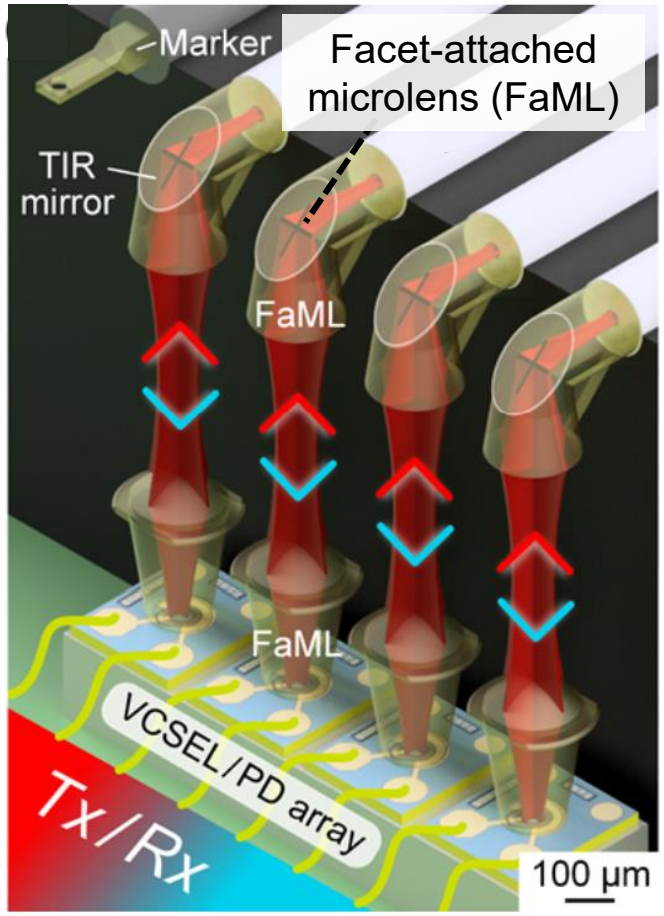


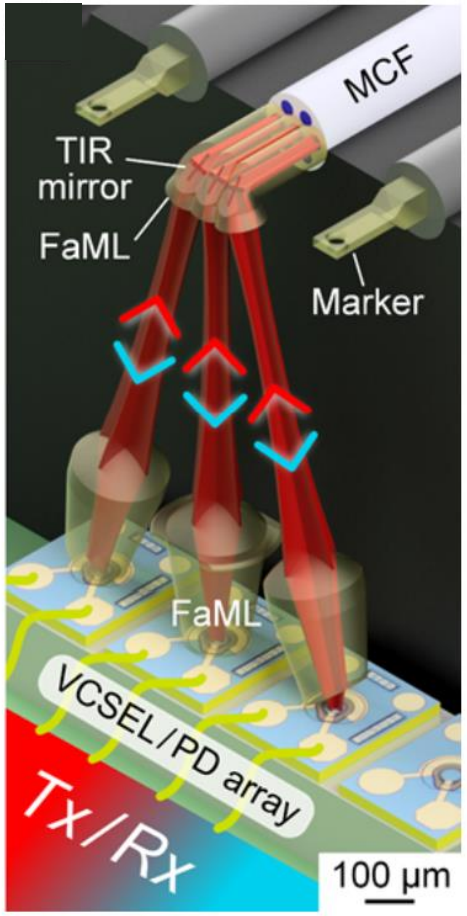


Dietrich *et al.*, Nat. Photon. **12**, 241–247 (2018)
Maier *et al.*, Opt Express **30**, 46602 – 46625 (2022)

FaML-based optical assemblies







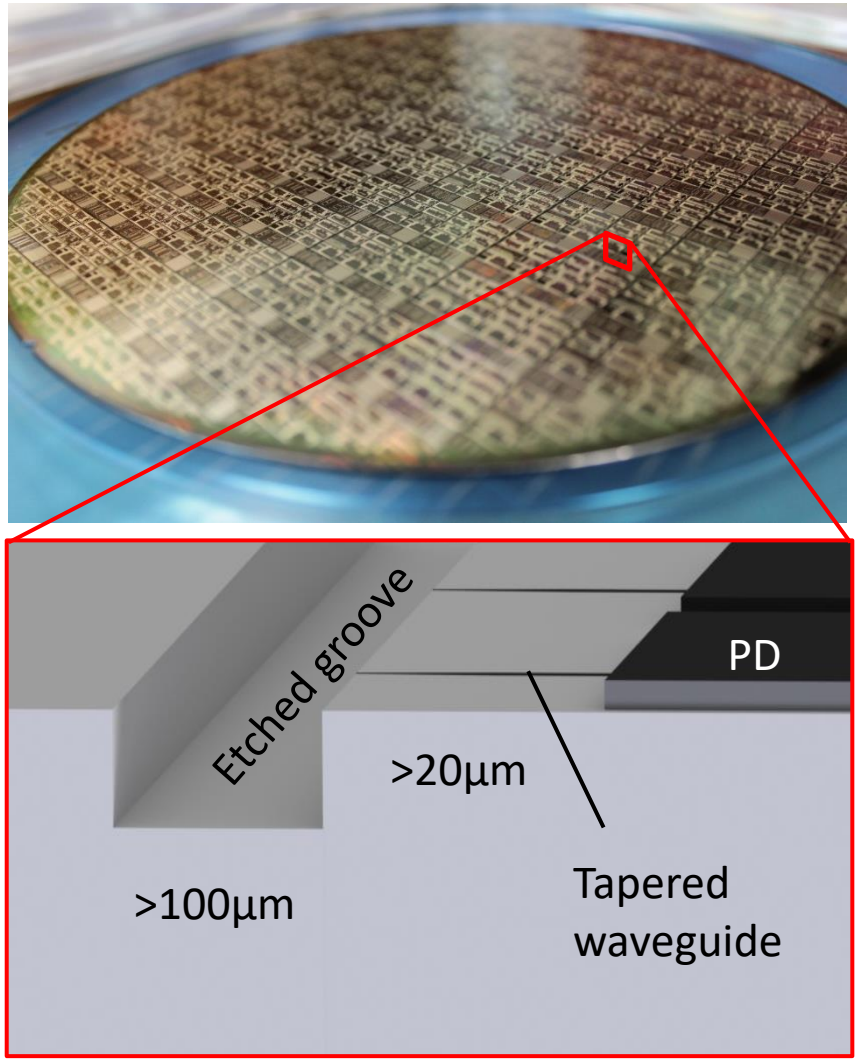
Examples:

- Combining PIC with discrete micro-optical elements, e.g, polarization beam splitters (PBS)
- Micrometer-scale alignment tolerances allow for passive assembly
- Vertical coupling of light within optical assemblies

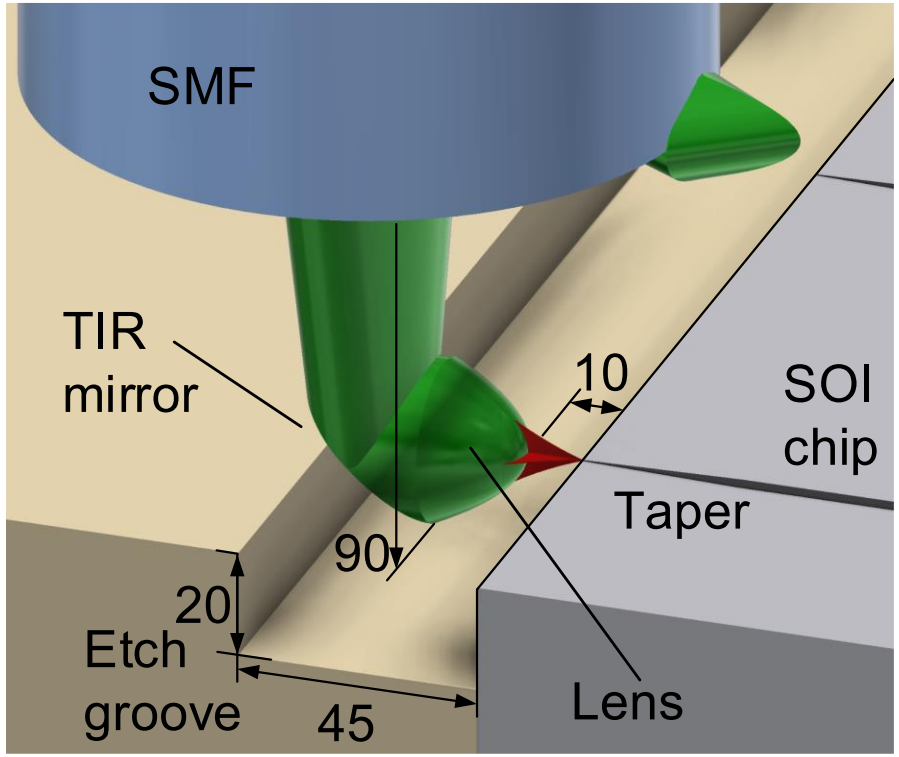
Maier *et al.*, Opt. Express **30**, 46602-46625 (2022)
Xu *et al.*, Light: Advanced Manufacturing **4**, 1-17 (2023)

Wafer-level probing

Challenge: Probing of edge-emitting devices prior to separation



Printing of **3D freeform facet-attaced elements** for wafer-level probing



Reproducibility: ± 0.2 dB

Trappen *et al.*, Opt. Express **25**, 37996 – 38007 (2020)

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www.silorix.com

www.luxtelligence.ai

www.vanguard-automation.com

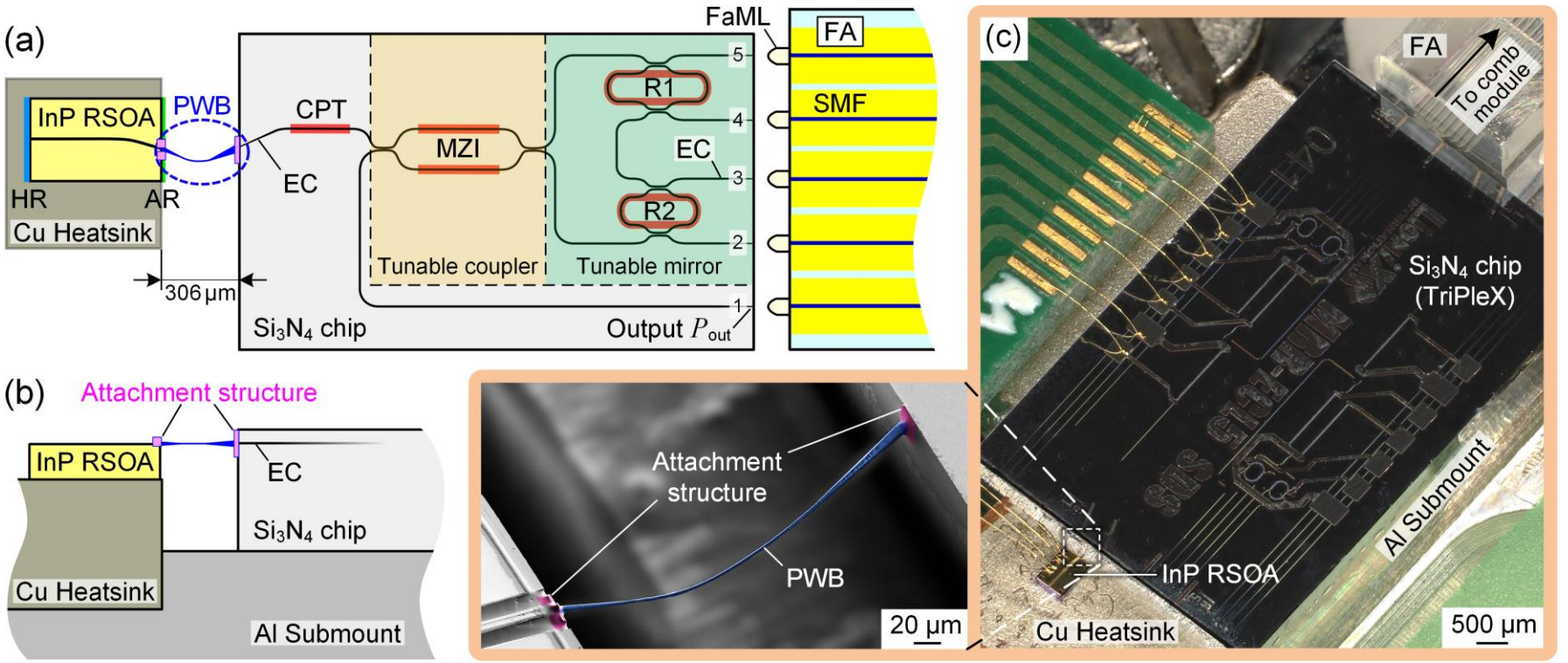
www.keystone-photonics.com

www.deeplight.ai

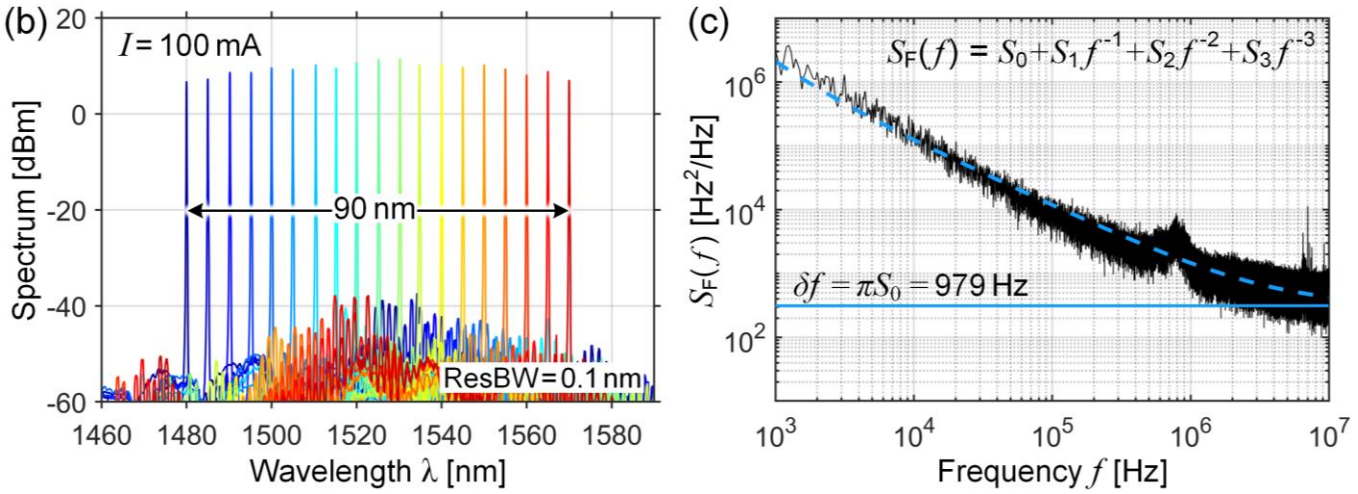
www.teragear.ai

Summary

PWB-based external-cavity laser (ECL) with Si_3N_4 PIC

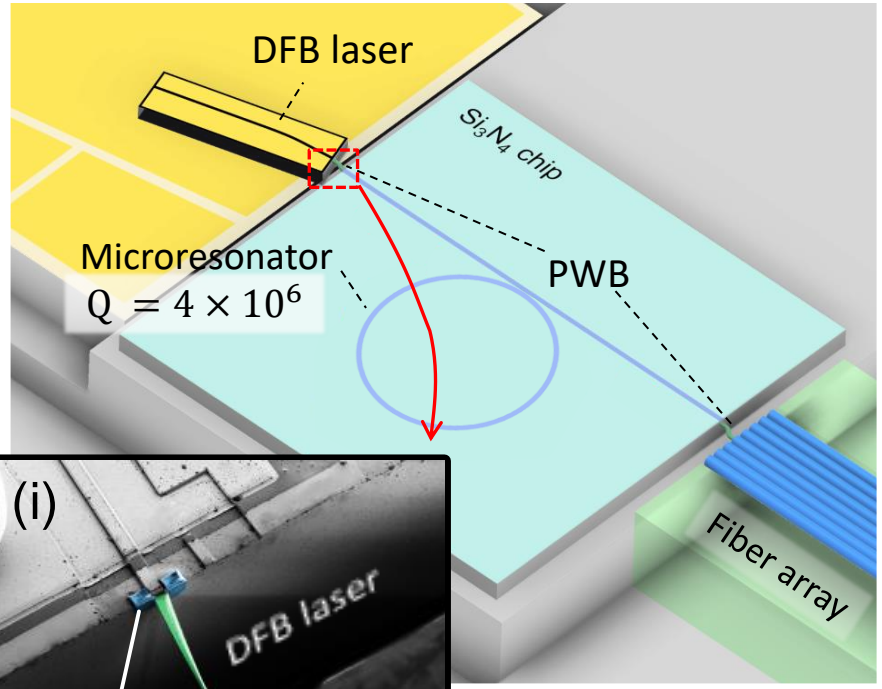


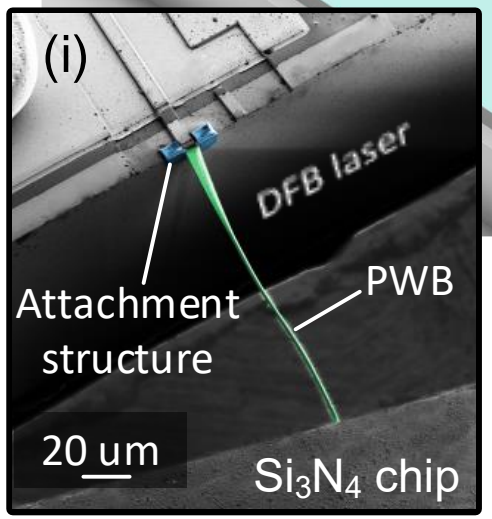
Sub-kHz intrinsic linewidth!

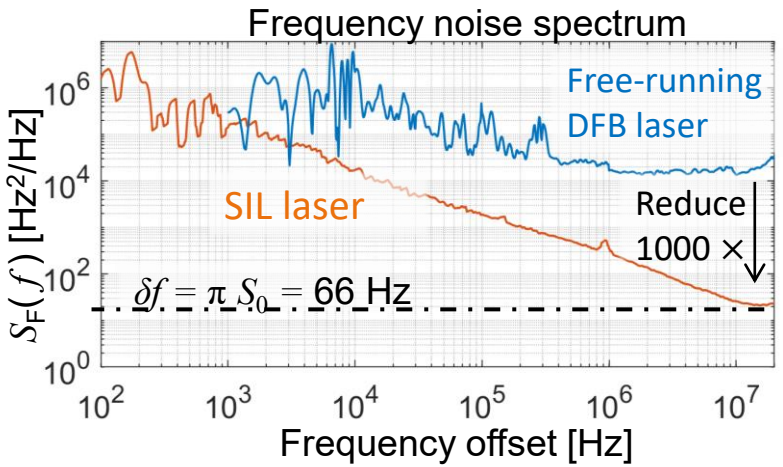


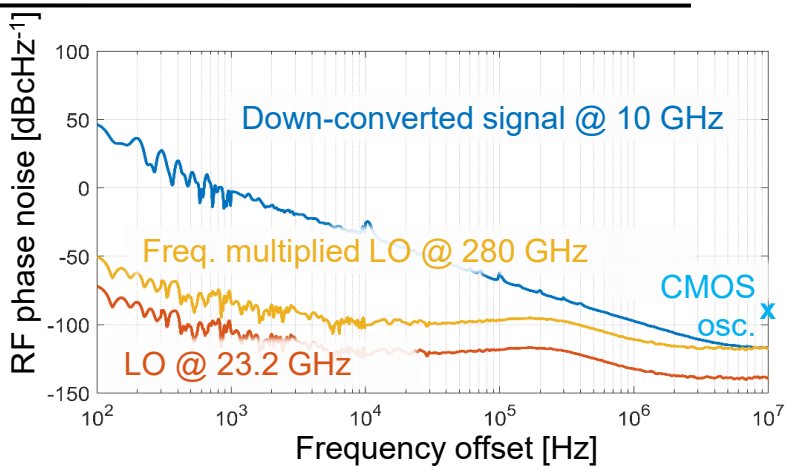
Maier *et. al.*, J. Lightw. Technol. **41**, 3479–3490 (2023)

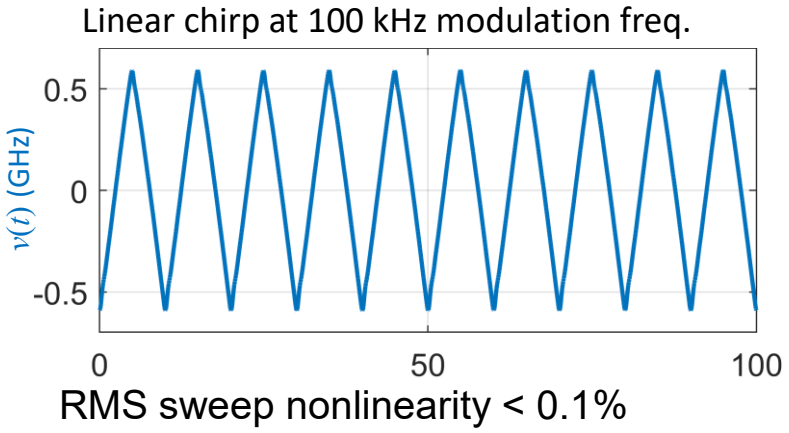
Hybrid Photonic Integration, Organic Electro-Optic Devices, and Frequency Combs

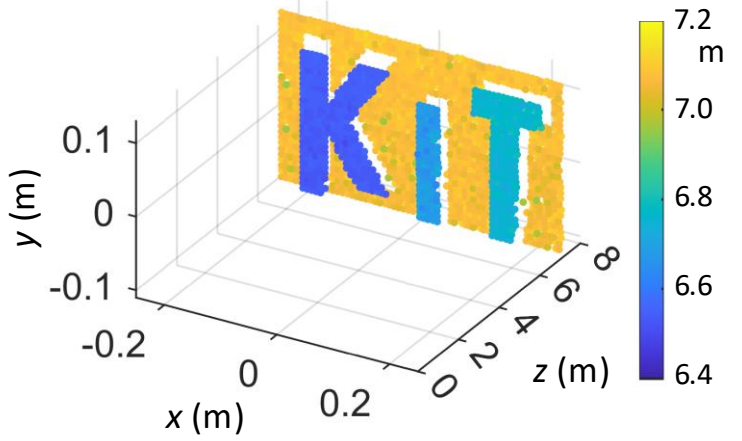




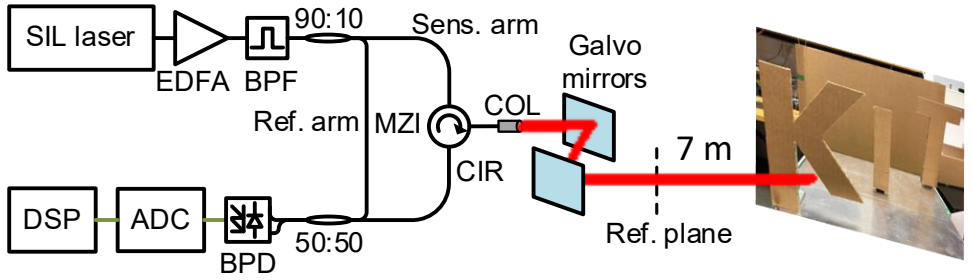






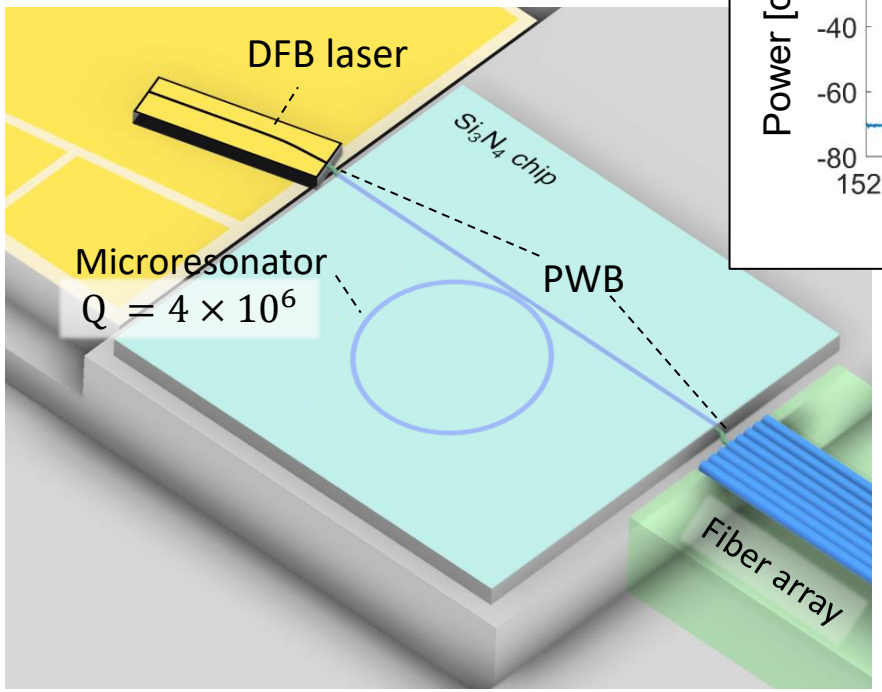


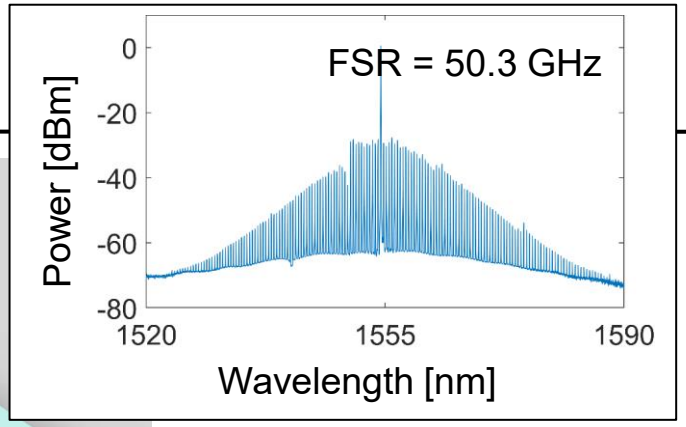
- ≤ 70 Hz intrinsic optical linewidth
- Fast linear frequency sweep for FMCW LiDAR
- Generation of low-phase-noise THz tones by mixing of two SIL laser tones, spaced by 280 GHz => −115 dBcHz^{-1} @ 10 MHz offset, on par with ref. osc.

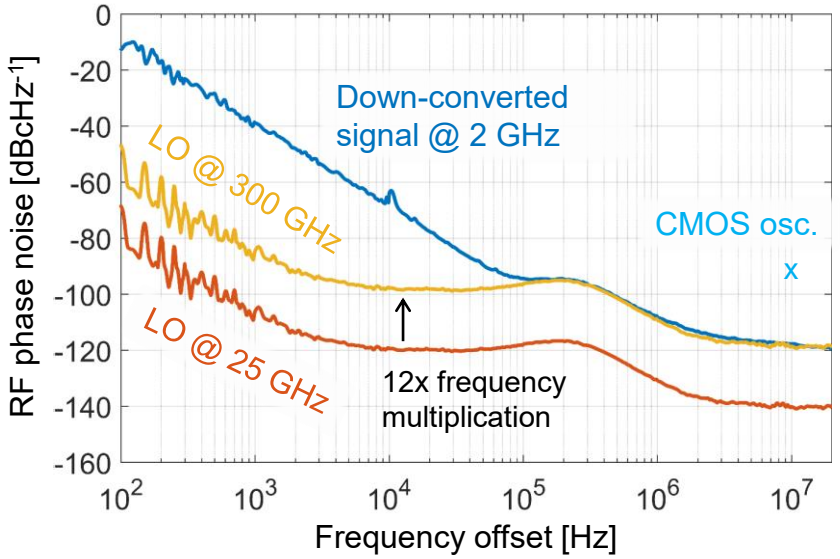


Chen *et al.*, Paper STu4P.4, CLEO 2023 Chen *et al.*, Paper SM2M.1, CLEO 2024

Kerr microcombs







- Generation of low-phase-noise THz tones at 300 GHz by photo-mixing of two comb lines
- Measured phase noise dominated by electrical signal generator
- Demonstration of wireless data transmission:
  - 250 Gbit/s @ 300 GHz over > 50 m
  - THz spread-spectrum transmission: 250 MBd signal spread over 50 GHz @ 300 GHz center frequency (23 dB processing gain)

Chen *et al.*, CLEO 2023, Paper STh3J.1
Fang *et al.*, ECOC 2024, Paper Thu3F.3

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www.silorix.com

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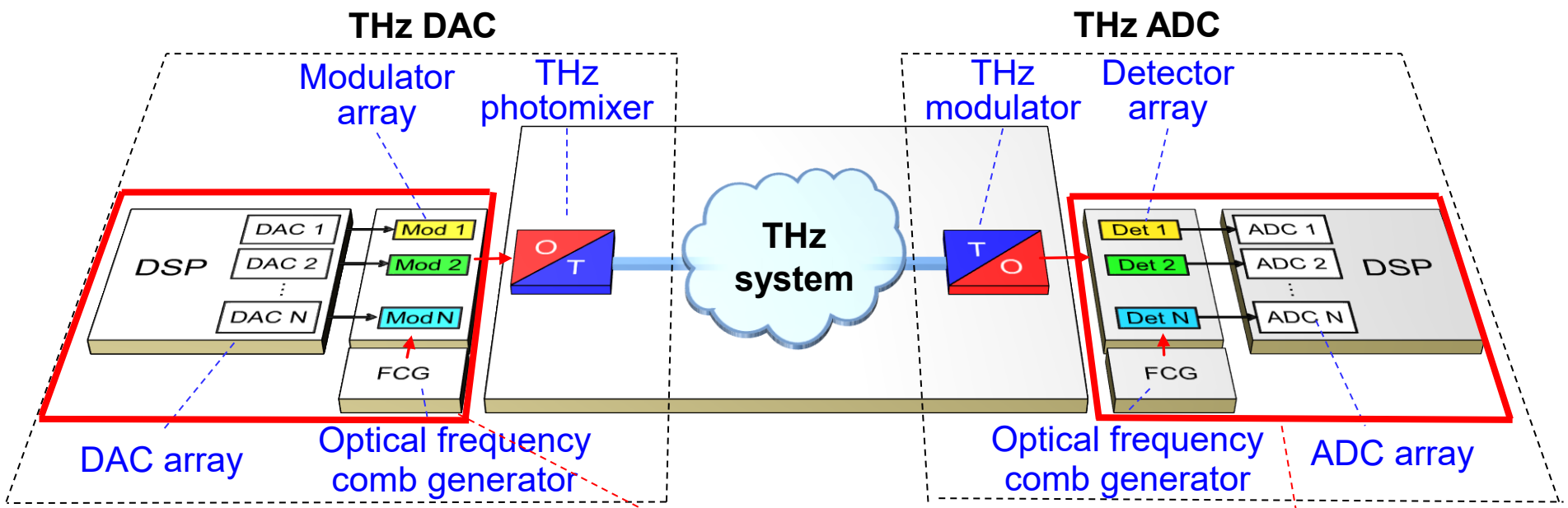
www.keystone-photonics.com

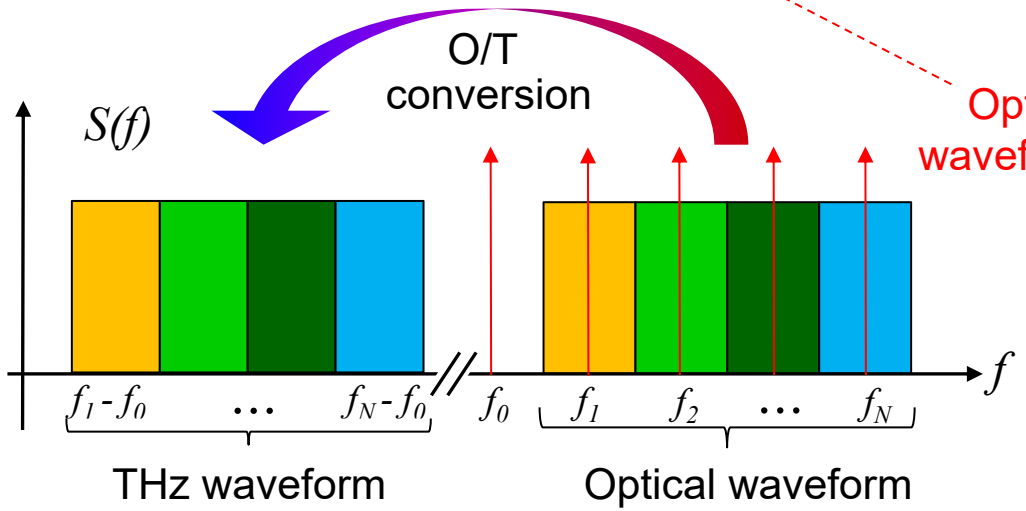
www.deeplight.ai

www.teragear.ai

Summary

Ultra-broadband photonic-electronic signal processing based on optical frequency combs



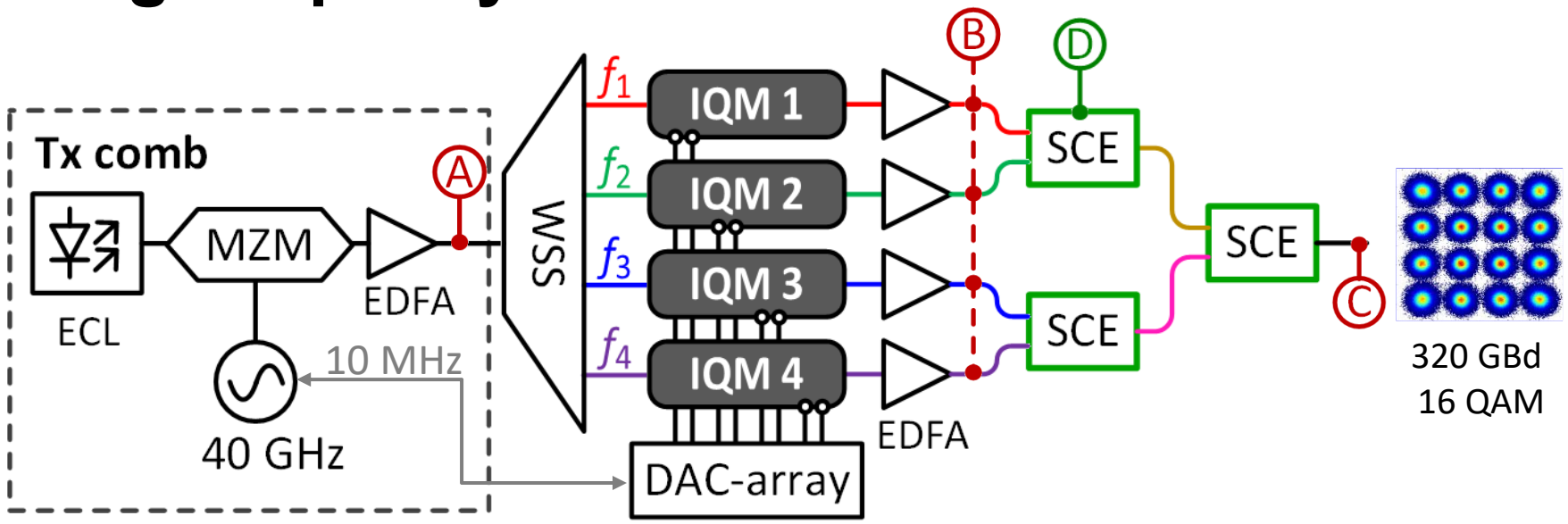


Optical arbitrary waveform generation (OAWG)

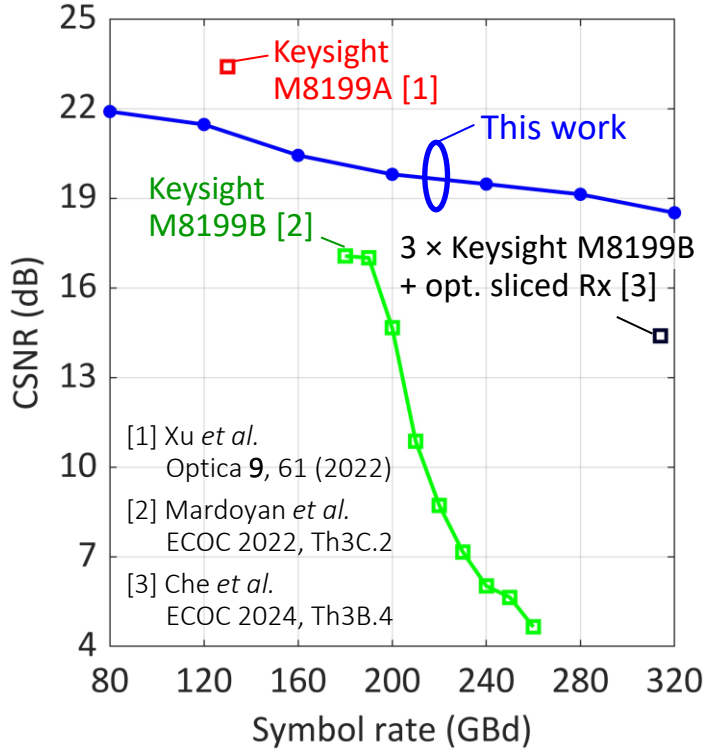
Optical arbitrary waveform measurement (OAWM)

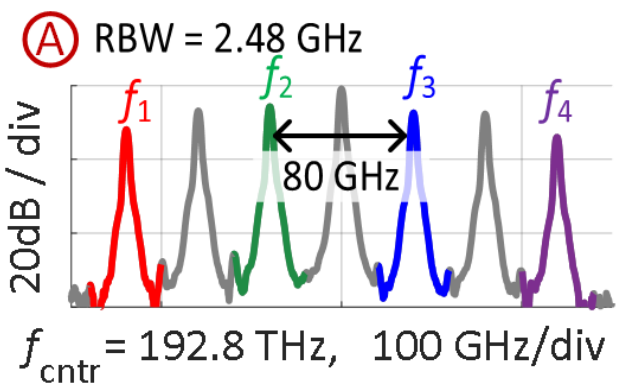
Drayss *et al.*, Light Sci. Appl. **14**, 353 (2025)
Fang *et al.*, Light Sci. Appl. **14**, 241 (2025)

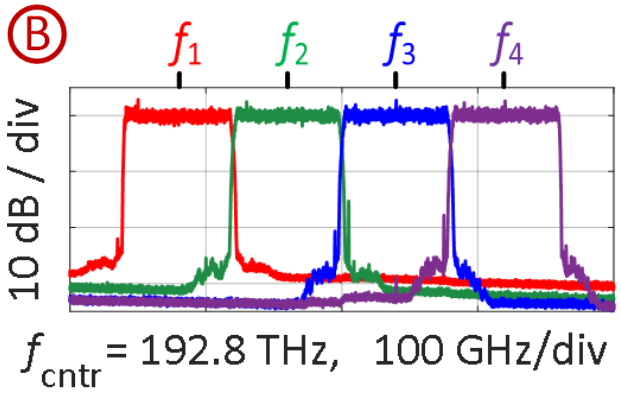
Optical Arbitrary Waveform Generation (OAWG) using Frequency Combs

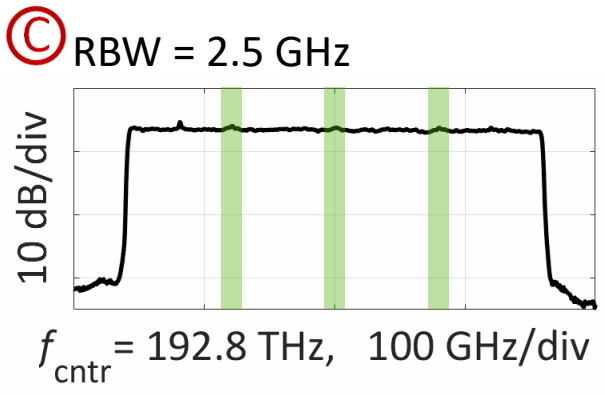


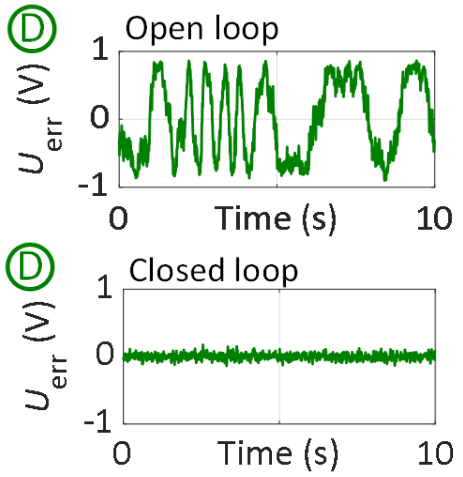
Signal quality:







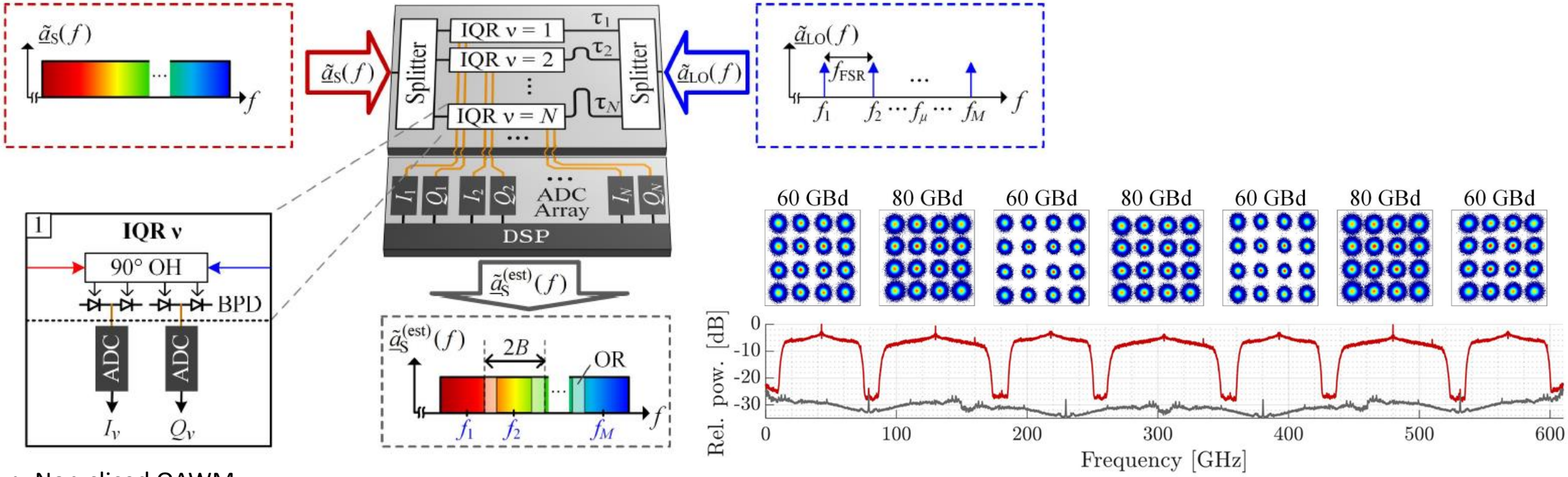




- First demonstration of spectrally sliced signal synthesis using four actively phase-stabilized tributaries
- Record-high bandwidth of 325 GHz

Drayss *et al.*, J. Light. Technol. **43**, 6349 – 6360 (2025)
Drayss *et al.*, Light Sci. Appl. **14**, 353 (2025)

Optical Arbitrary Waveform Measurement (OAWM)

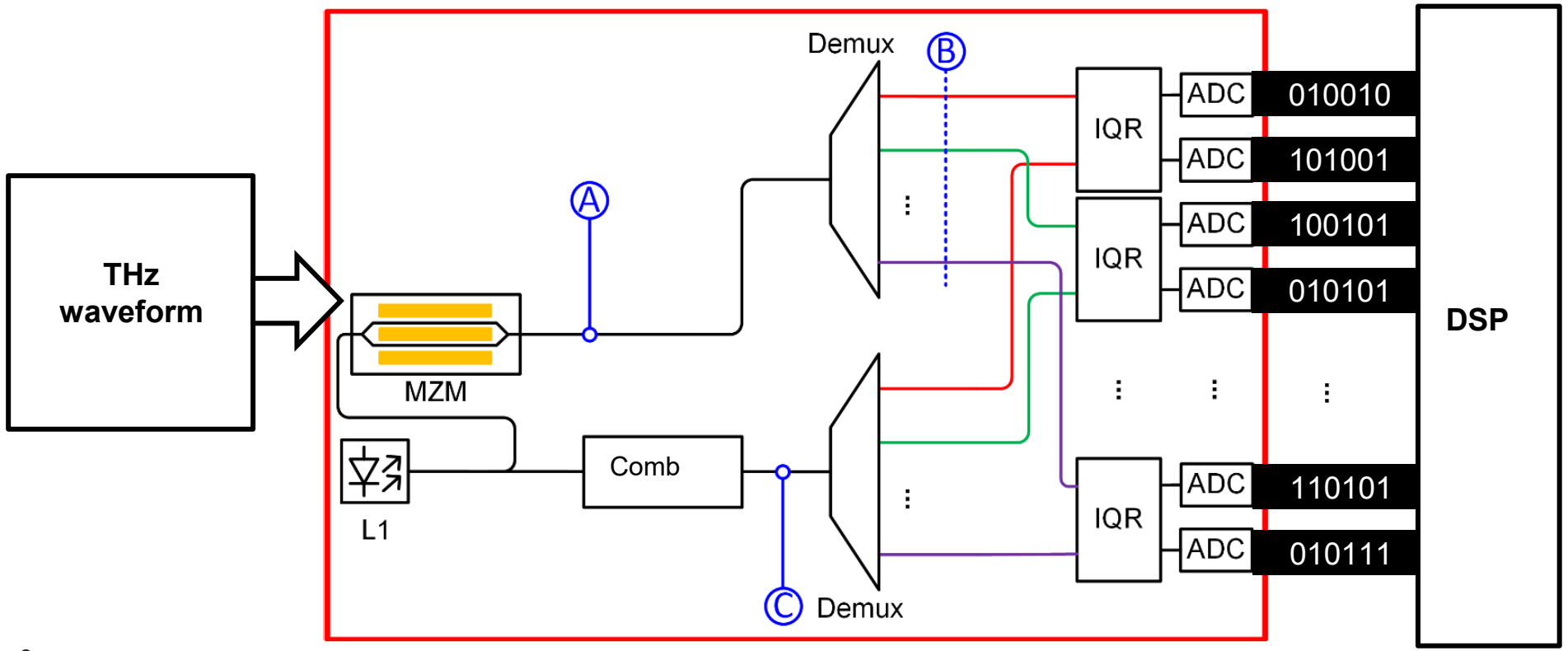


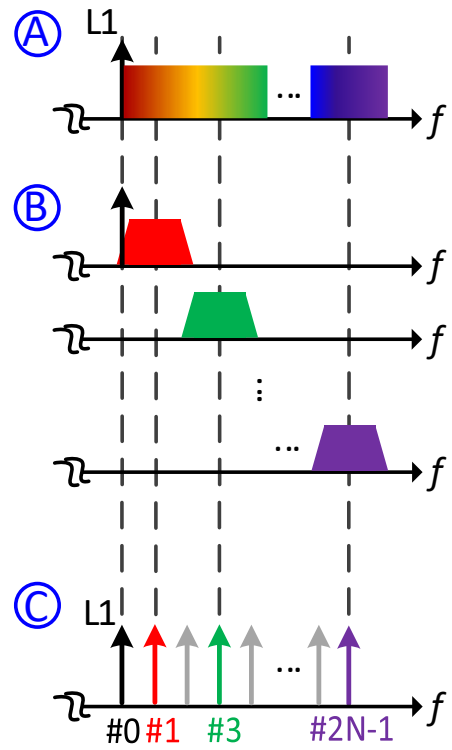
- Non-sliced OAWM
- Detailed mathematical model for signal reconstruction
- 4 LO tones with 150 GHz FSR
- Demonstration: Simultaneous acquisition of 16QAM and 64QAM WDM channels over up to 600 GHz
- Largest bandwidth so far demonstrated in an OAWM experiment

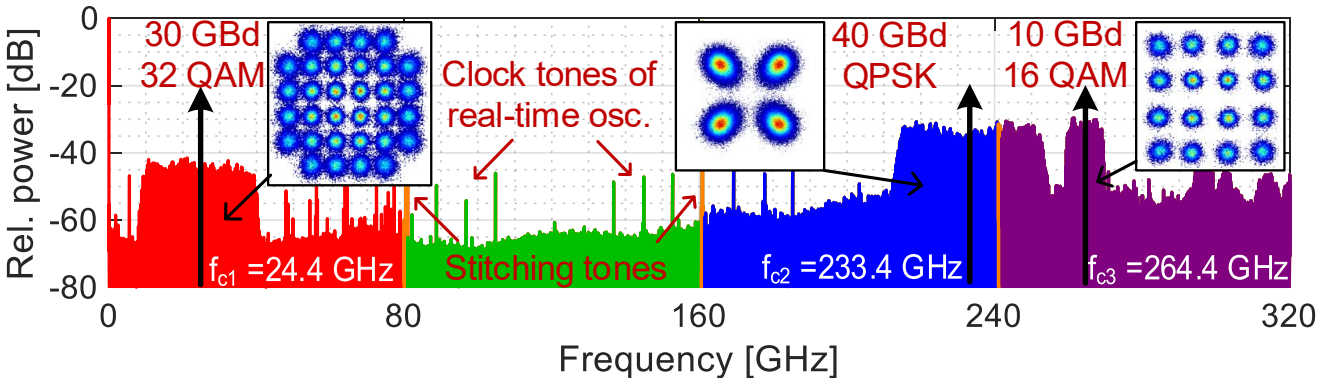
Drayss *et al.*, Optica **10**, 888-896 (2023)
Drayss *et al.*, J. Light. Technol. **42**, 4733 – 4750 (2024)

Photonic-Electronic Analogue-to-Digital Converter (PE-ADC)

Concept: Electro-optic conversion + optical arbitrary waveform measurement using optical frequency combs as multi-wavelength local-oscillators







⇒ Highest bandwidth achieved so far for an ADC (independently of the implementation)

Fang *et al.*, Light Sci. Appl. **14**, 241 (2025)

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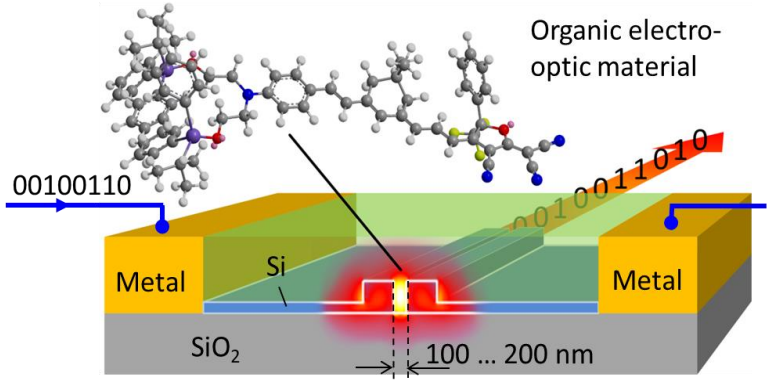
Summary

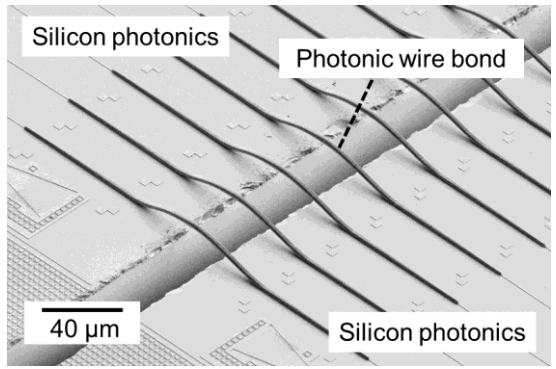
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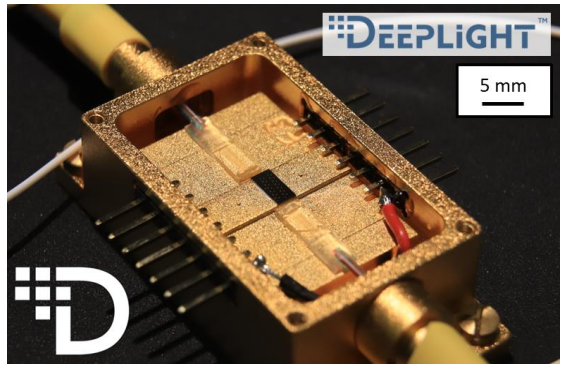
- The performance of AI superclusters is mainly limited by insufficient communication bandwidth.

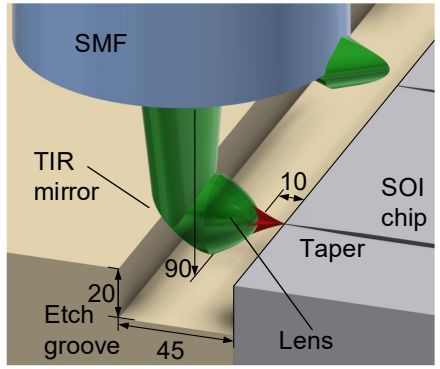


- Integrated photonics is a key enabler for these bottlenecks, but substantial technological progress is still required on all levels.









- This requires close and efficient collaboration between excellent fundamental research and innovative industrial applications, e.g., through (university) start-ups.

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