Silicon-organic hybrid electro-optic modulators for next generation optical interconnects

A. Mertens, SilOriX GmbH

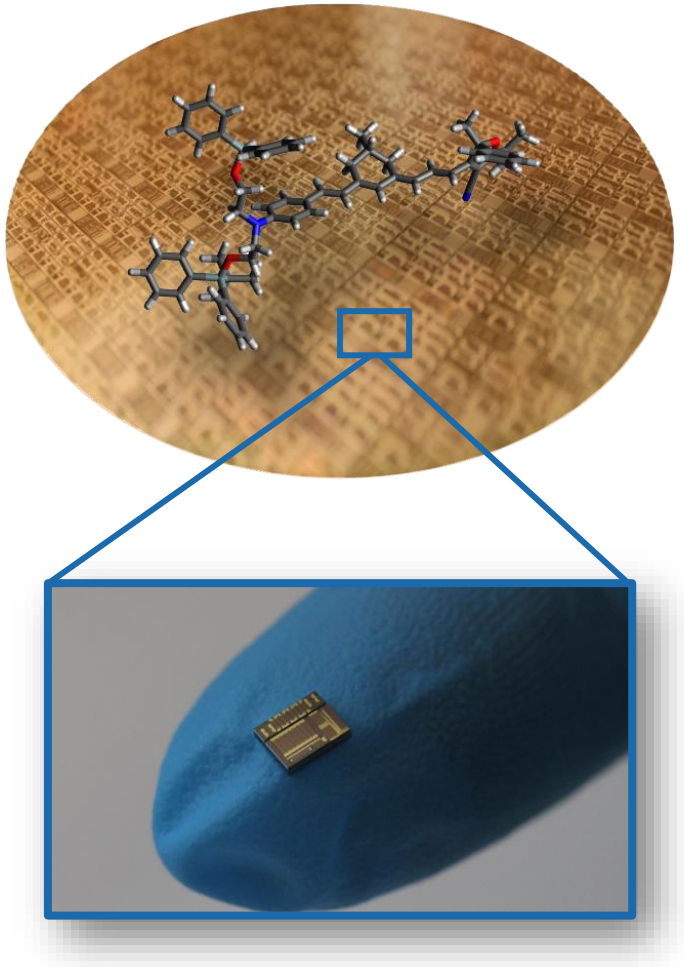
SilOriX: Mission & Vision

Mission

SilOriX delivers components for energy-efficient electro-optic conversion of signals in high-speed communication networks.
Our mission is to provide scalable and sustainable solutions by enhancing silicon photonics through engineered organic materials.

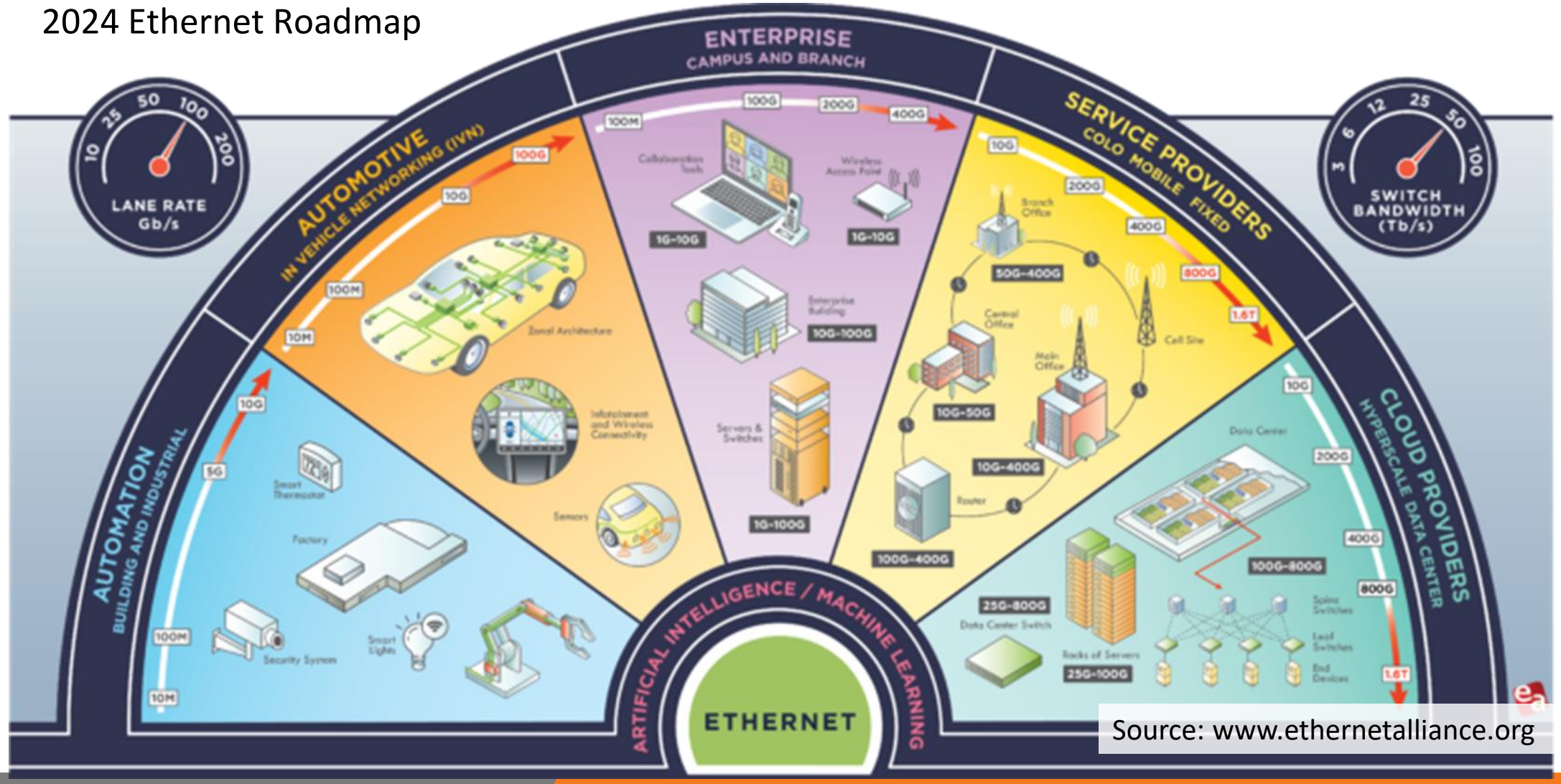
Vision

SilOriX will become the technology leader and global supplier of silicon-organic hybrid (SOH) photonic integrated circuits (PIC).



Application pull:
Scalable optical communication networks

2024 Ethernet Roadmap



Source: www.ethernetalliance.org

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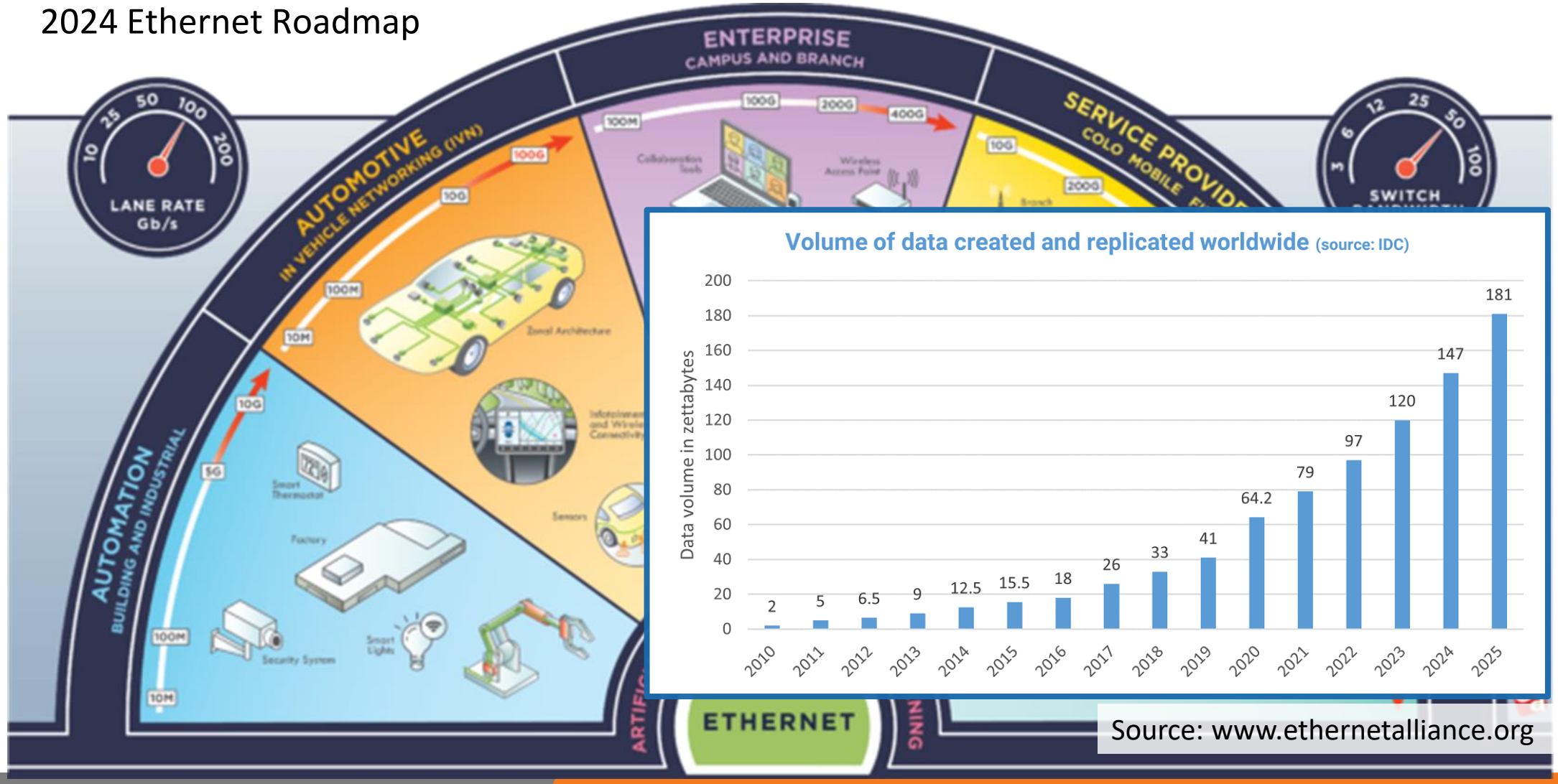

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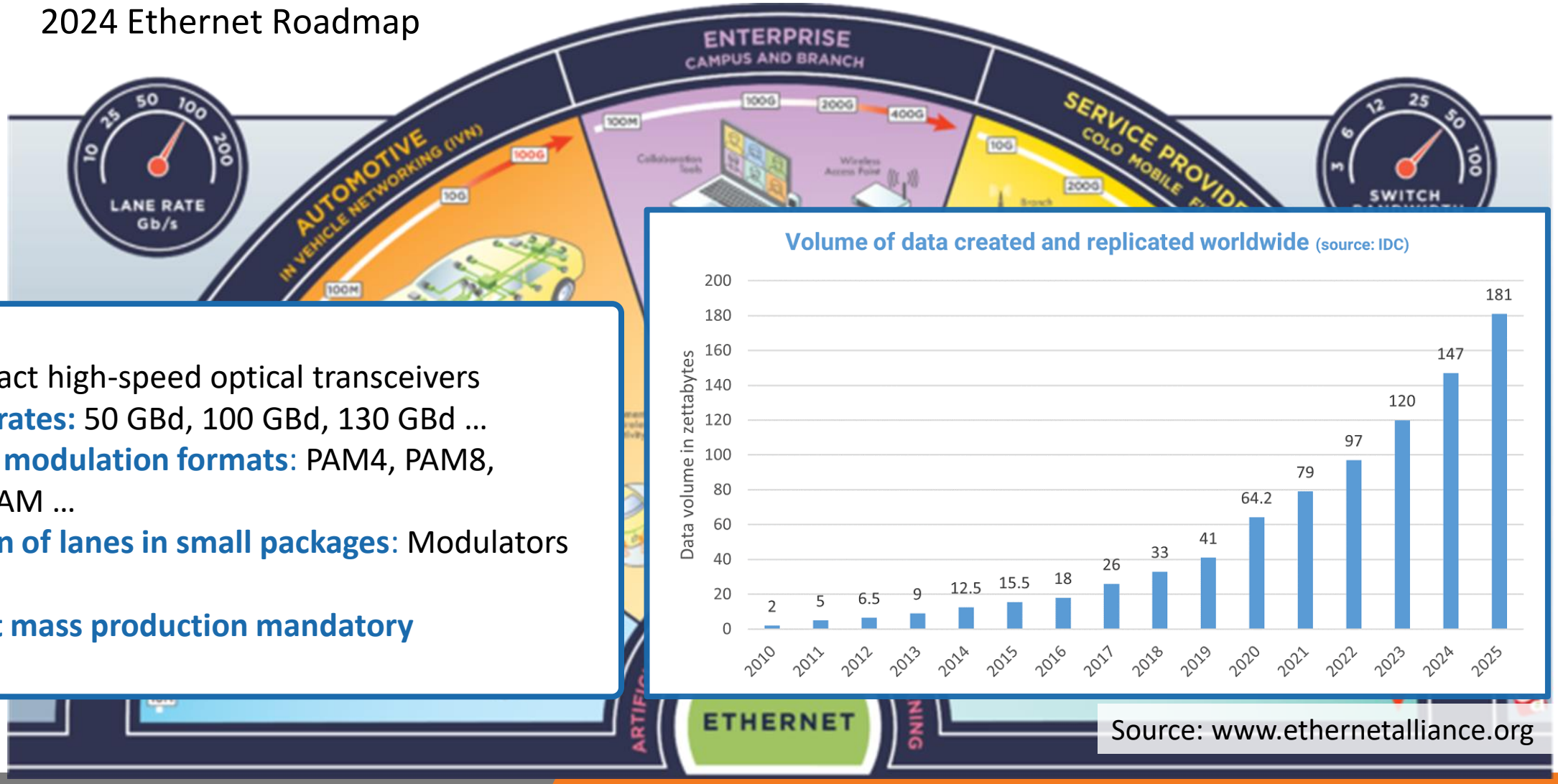

Needed: Compact high-speed optical transceivers

- **High symbol rates:** 50 GBd, 100 GBd, 130 GBd …
- **Higher-order modulation formats**: PAM4, PAM8, 16QAM, 32QAM …
- **Parallelization of lanes in small packages**: Modulators with low $U_\pi L$
- **Cost-efficient mass production mandatory**

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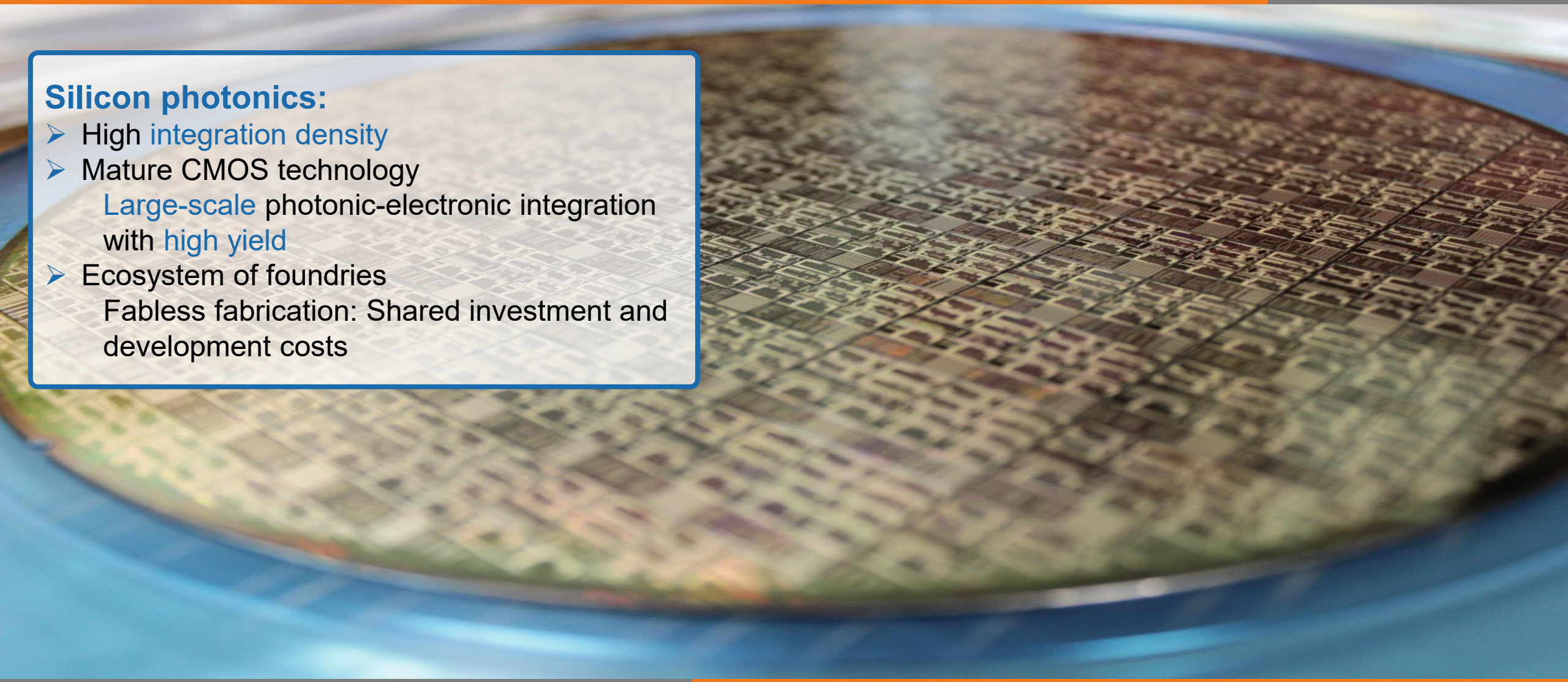
Technology push: Silicon photonics



Silicon photonics:

- High integration density
- Mature CMOS technology
  - Large-scale photonic-electronic integration with high yield
- Ecosystem of foundries
  - Fabless fabrication: Shared investment and development costs

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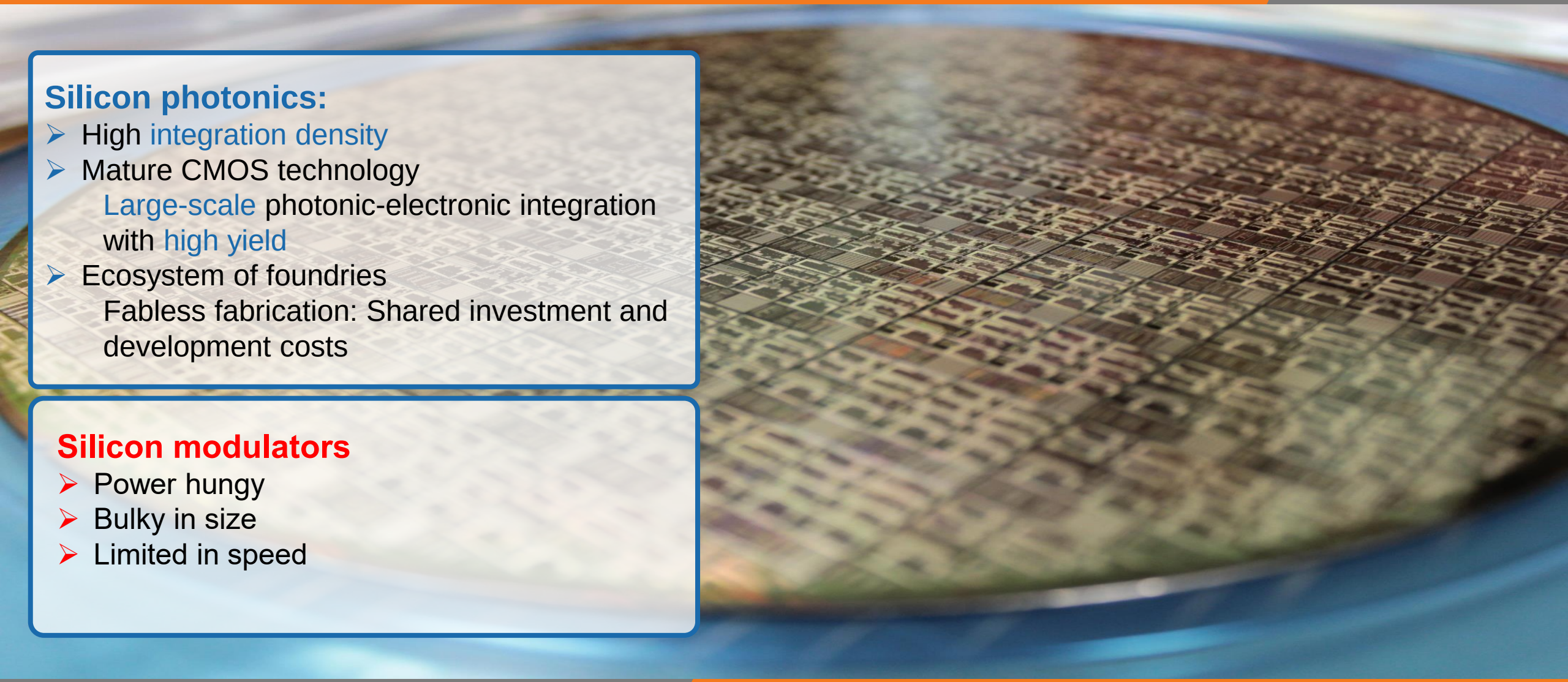

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Silicon modulators

- Power hungy
- Bulky in size
- Limited in speed

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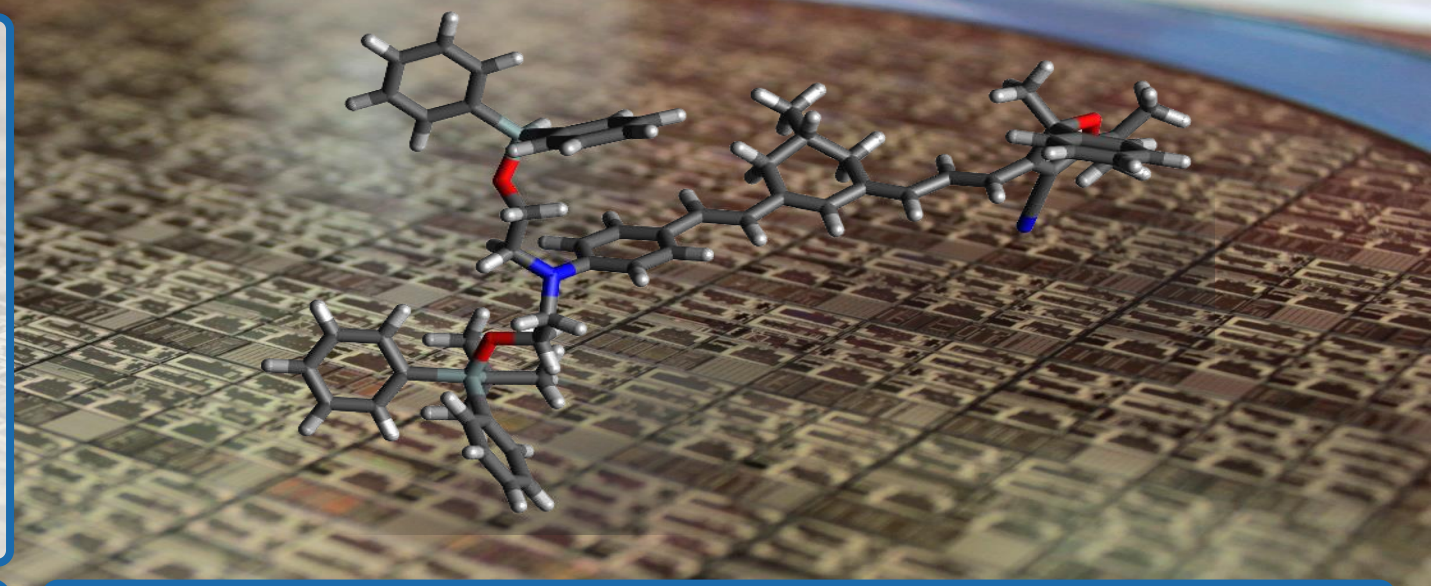

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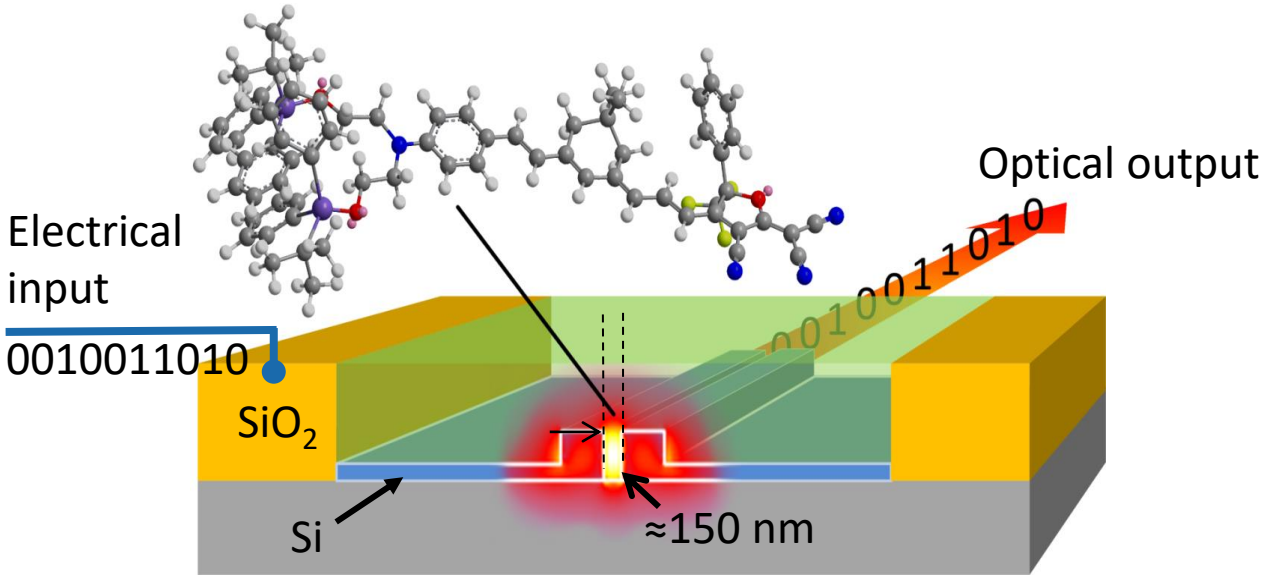
Electro-optic molecules

- Material-efficient solution processes (e.g. inkjet printing)
- High-performance (r_{33} beyond 100 pm/V)
- Tailor-made materials for various applications

SOH Technology: Performance



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

- High-performance: r_{33} = 390 pm/V, $U_\pi L \approx 0.3$ Vmm
- Energy-efficient: < **1 V_{pp}, few fJ/bit for Mach-Zehnder modulator**

Wolf *et al.*, Opt. Express **26**, 220-232 (2018)
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Schwarzenberger et al. OFC 2024, Post-Deadline-Paper Th4B.6

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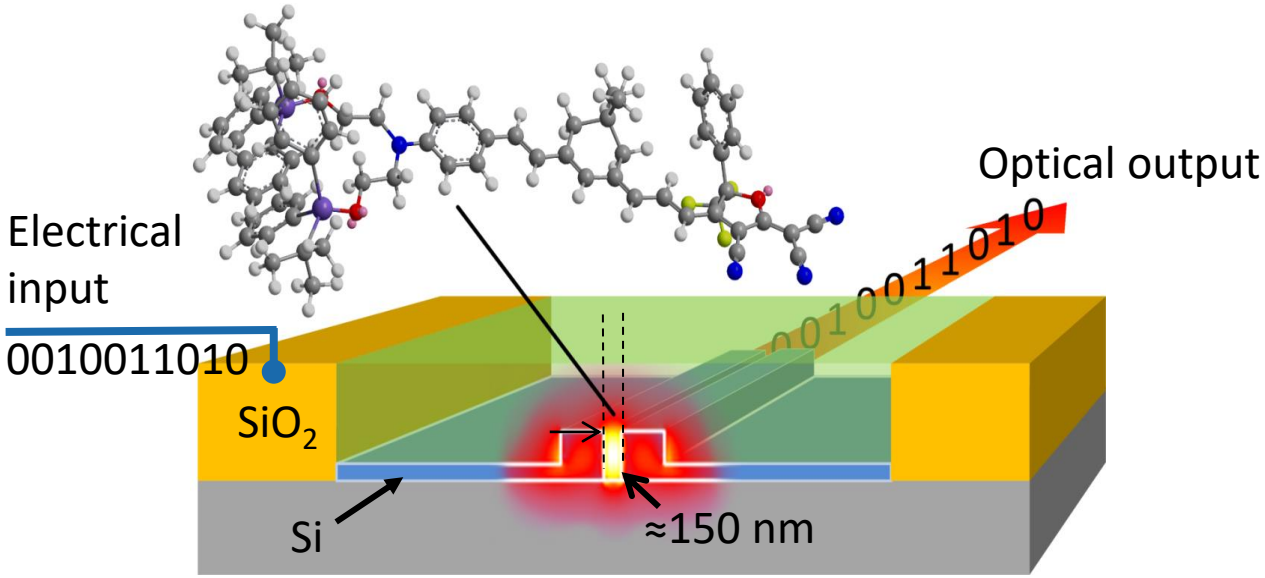

Concept: Combine silicon-on-insulator waveguides with organic electro-optic cladding material

- High-performance: r_{33} = 390 pm/V, $U_\pi L$ ≈ 0.3 Vmm
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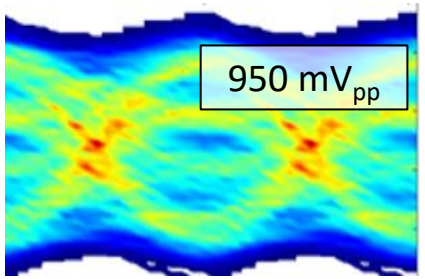
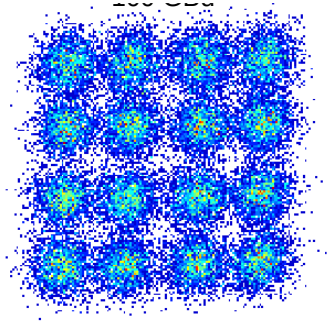
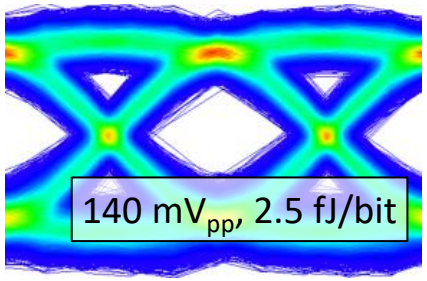
192 GBd PAM4 (384 Gbit/s)



100 GBd 16 QAM (400 Gbit/s per pol.)



40 Gbit/s OOK



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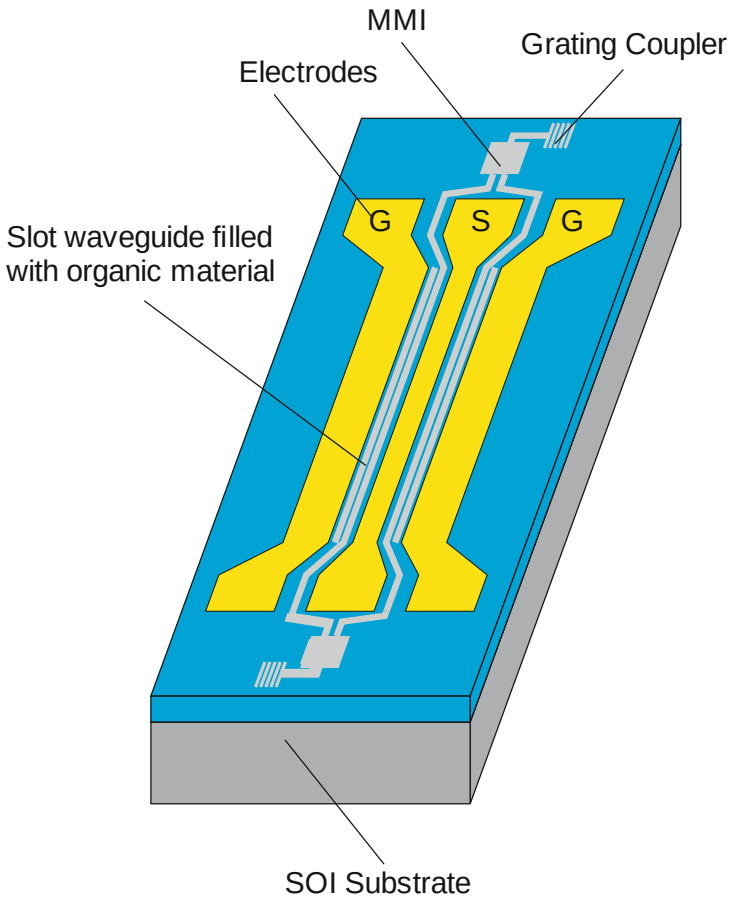
Core Technology:
Silicon-Organic Hybrid (SOH) Integration



- Basic silicon photonic waveguide structures fabricated in standard silicon photonic process along with full portfolio of other devices (SiGe detectors *etc.*)
  ⇒ High integration density, high yield

- Organic EO materials deposited and poled in a back-end post-processing step
  ⇒ No compatibility conflicts with front-end CMOS processing

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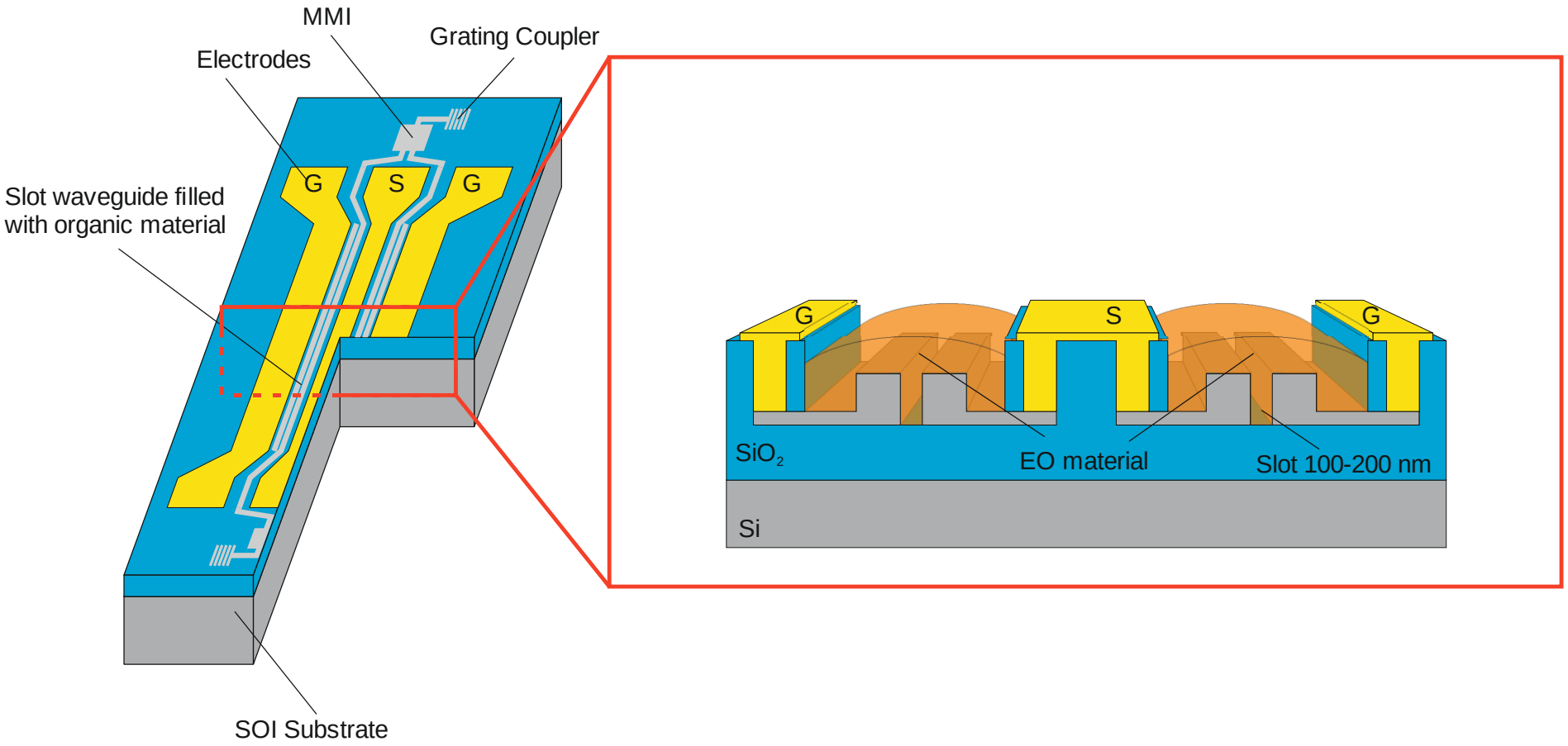

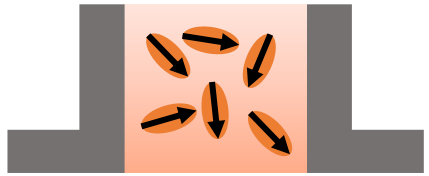

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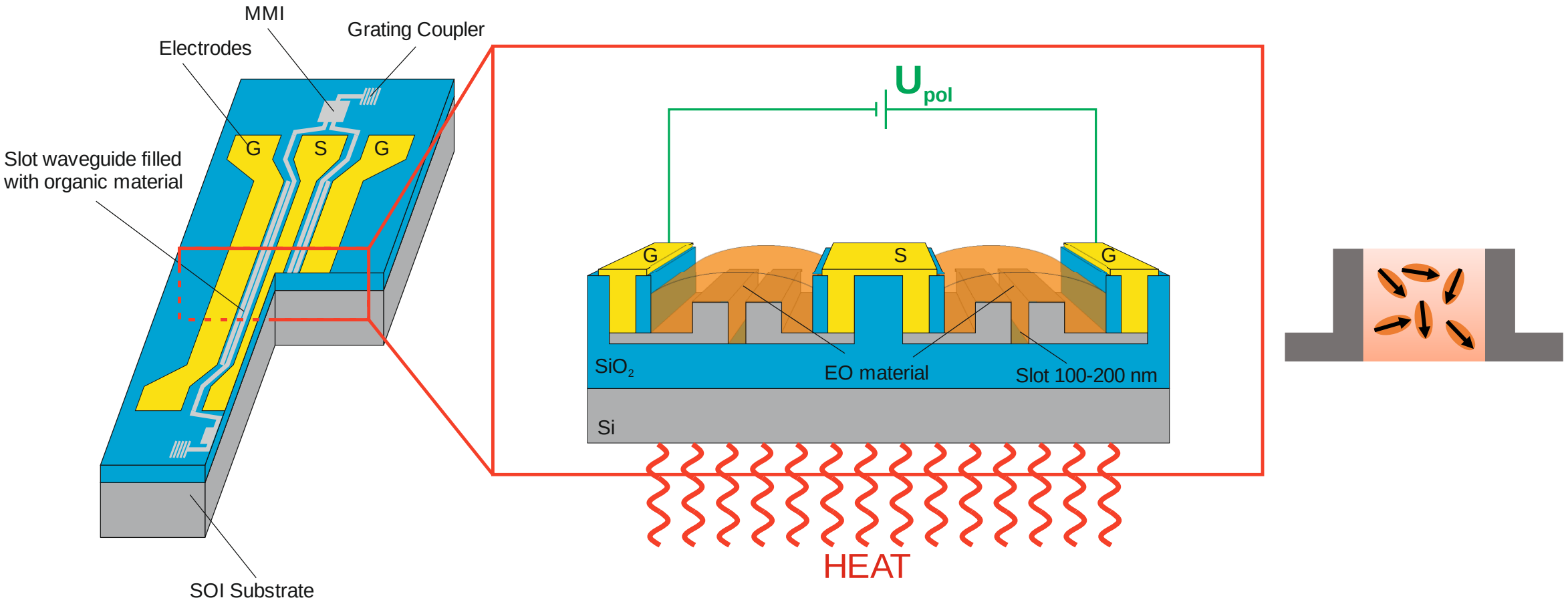

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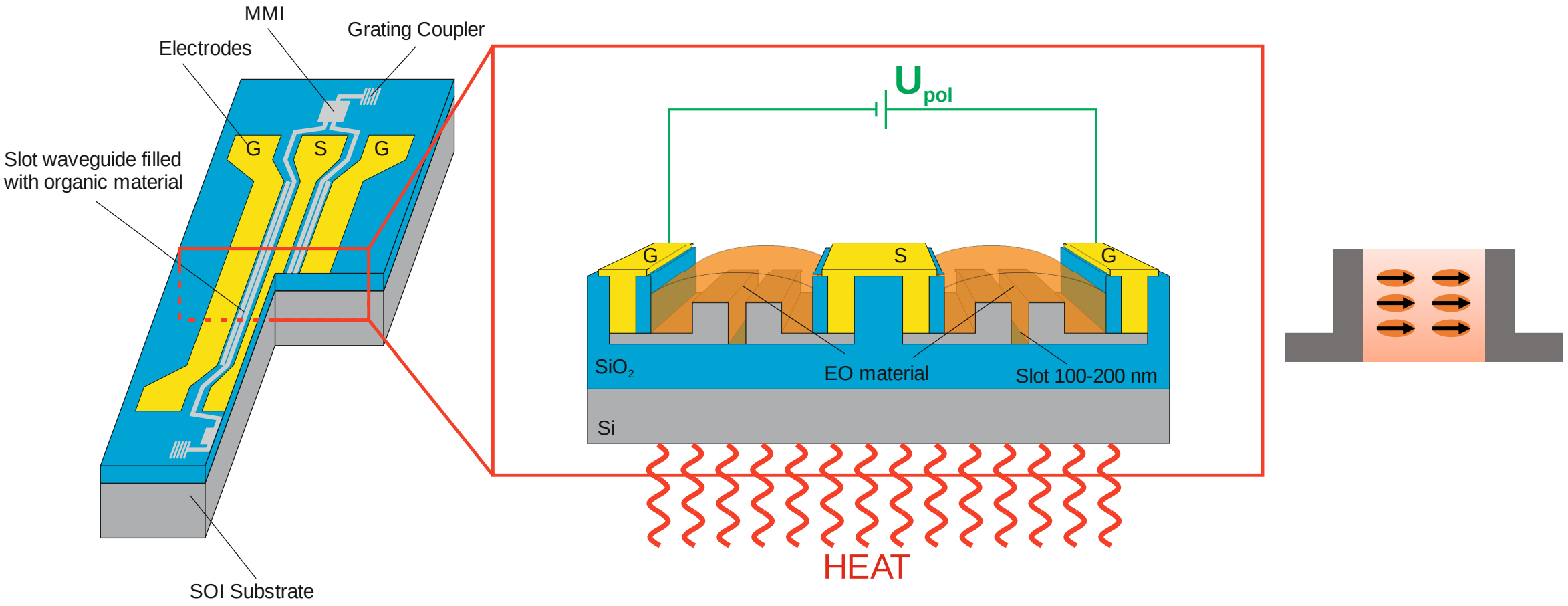

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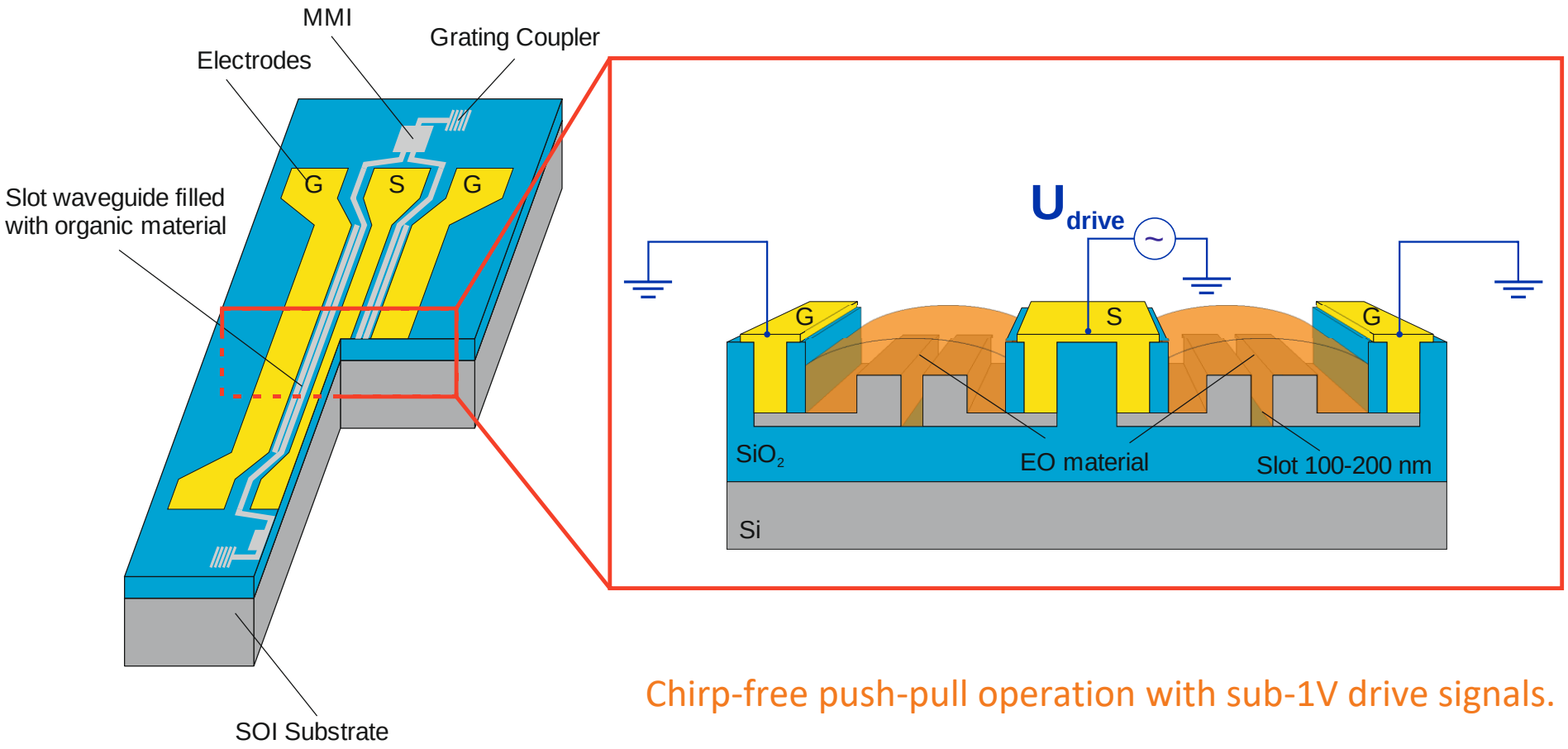

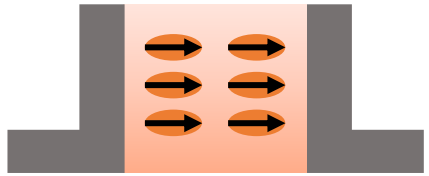

Chirp-free push-pull operation with sub-1V drive signals.

Tentative data sheet

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* × 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)
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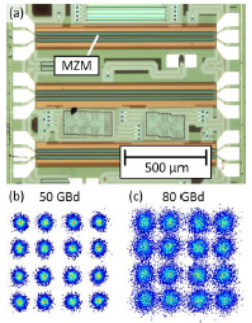

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DC π-voltage	0.5 ... 1.0 V
Electro-optic bandwidth	≥ 50 GHz @3 dB, ≥ 100 GHz @6 dB
On-chip optical loss	≤ 2 dB
DC extinction ratio	≥ 30 dB
Operating wavelengths	1250 nm ... 1450 nm 1350 nm ... 1550 nm 1450 nm ... 1650 nm
On-chip device footprint	≤ 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).
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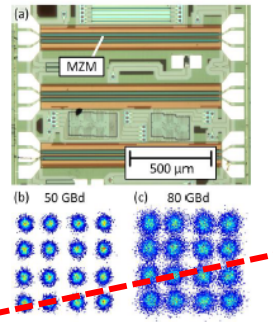

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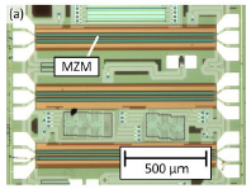

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Operating temperature[2]	-270 °C – 85 °C
Maximum optical input power	15 dBm

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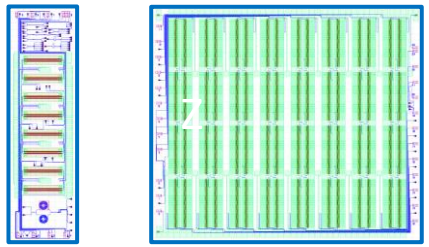
8 x SOH 8 x pn-type SiP



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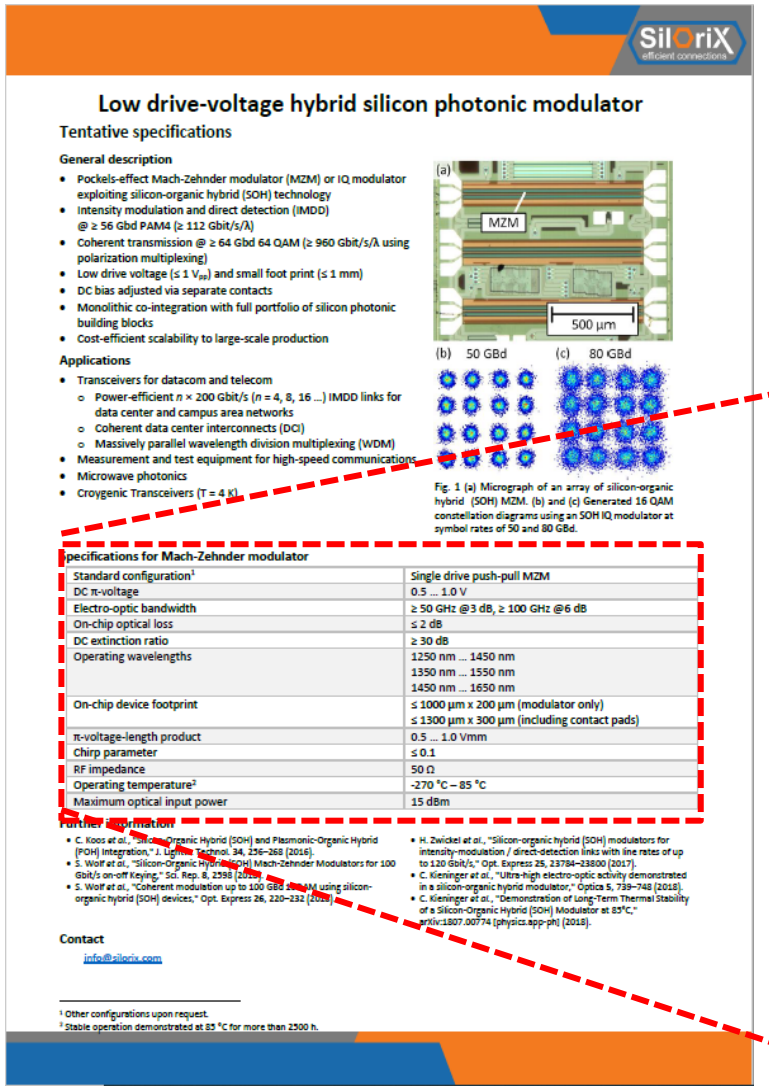

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(a) MZM 500 µm (b) 50 GBd (c) 80 GBd

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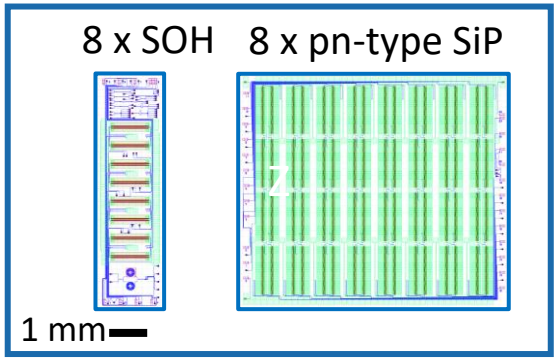
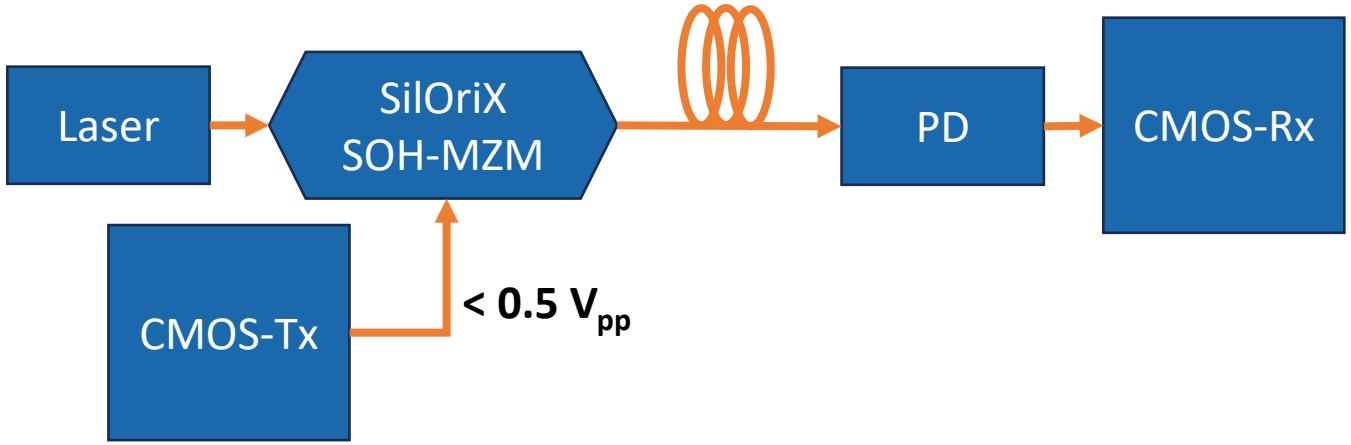
[1] Other configurations upon request.
[2] Stable operation demonstrated at 85 °C for more than 2500 h.



- Monolithic co-integration with standard silicon photonics
- Operation by standard "CMOS-signals" without drive amplifier

Standard configuration	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	1260 nm - 1625 nm (O band to L-band)
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	-270 °C – 85 °C
Maximum optical input power	15 dBm

Driver-less operation



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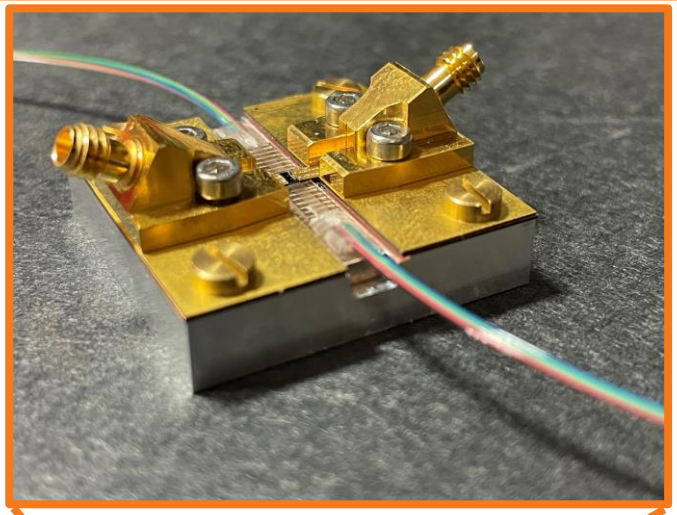
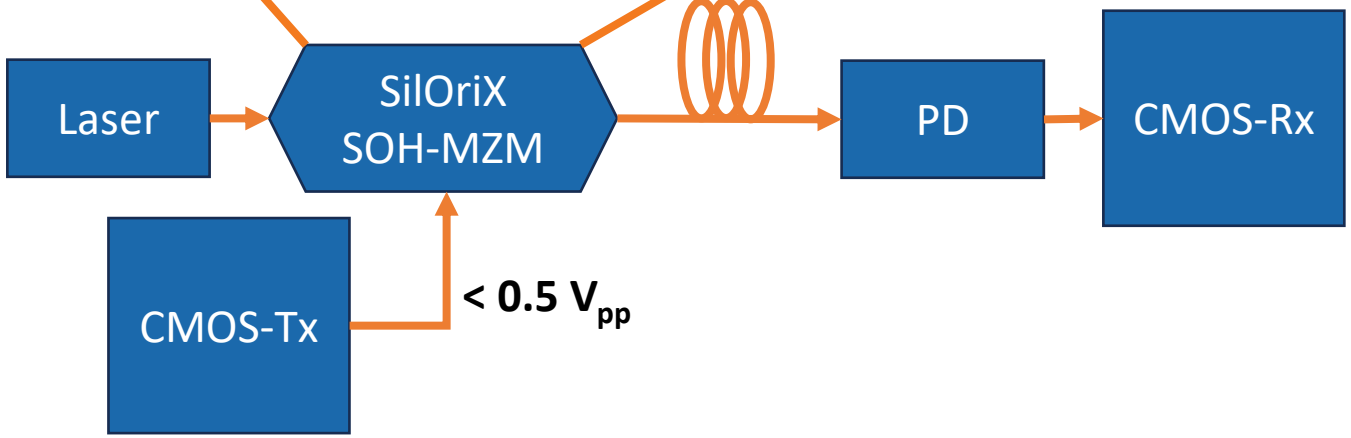
Driver-less operation





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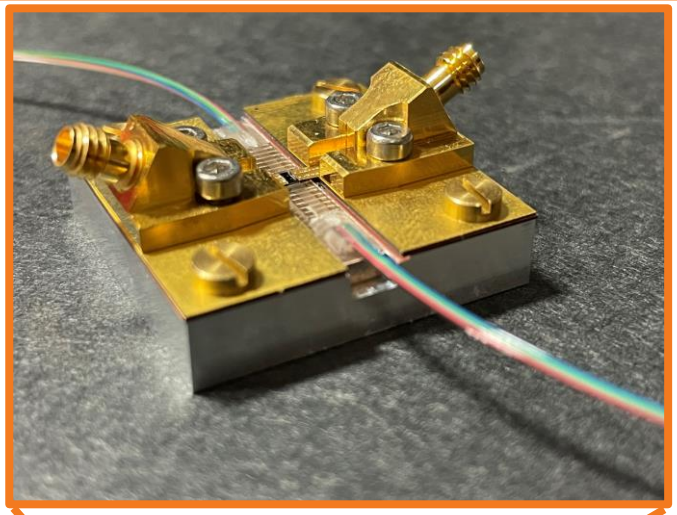
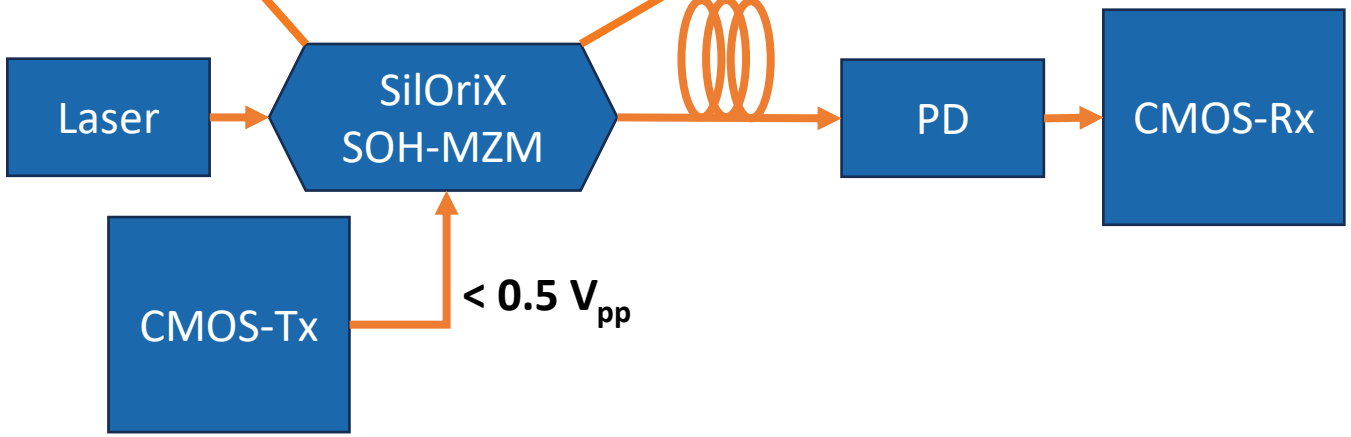
Driver-less operation





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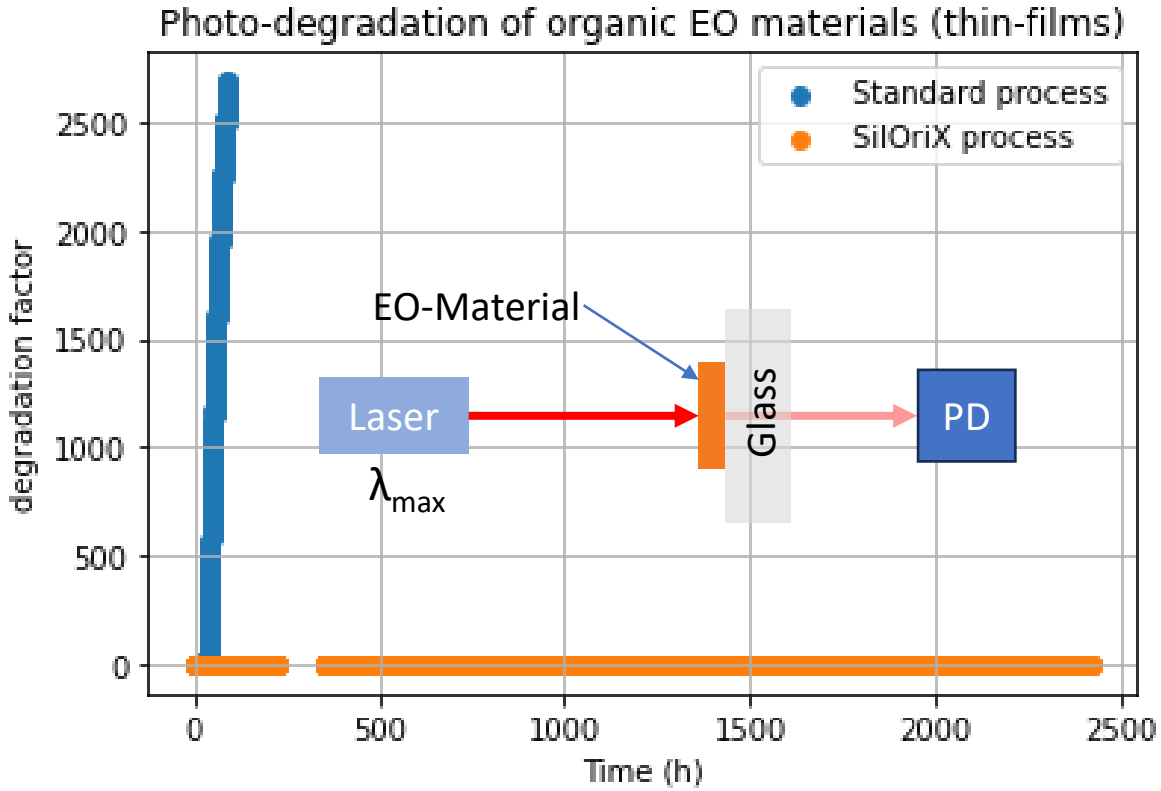
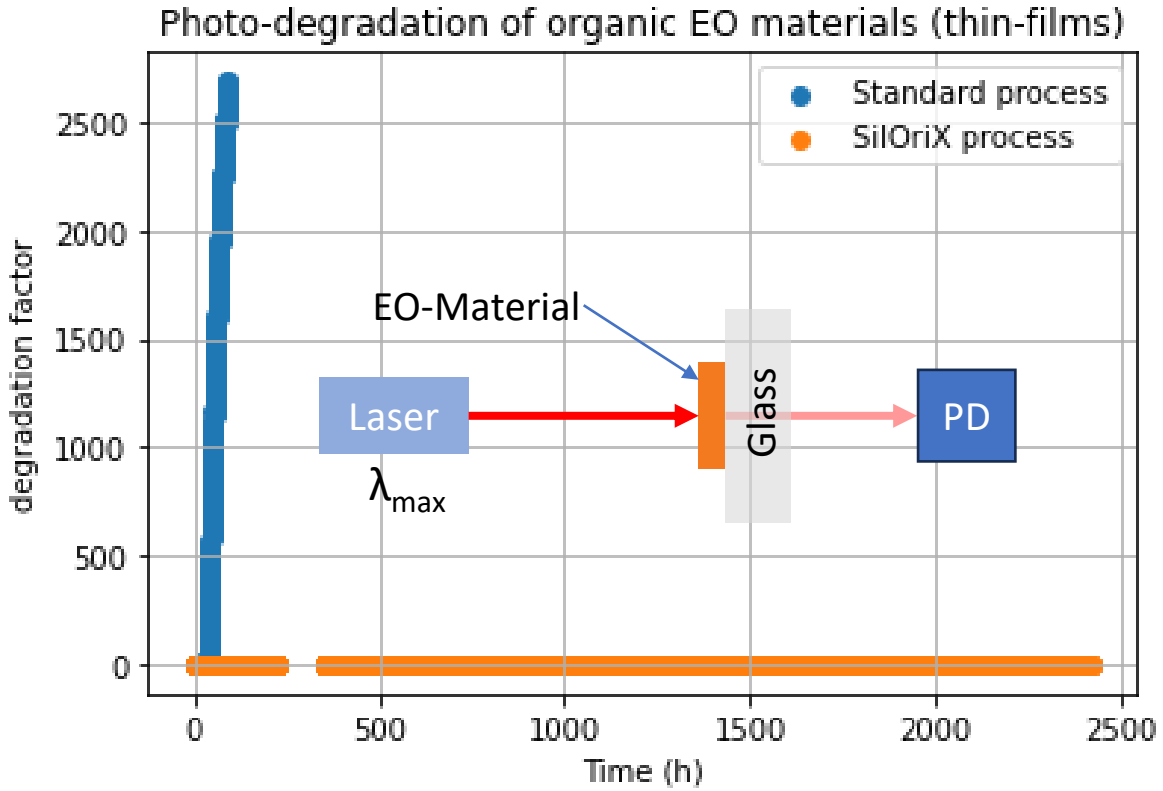
- Fully packaged SOH-modulator utilizing SilOriX's proprietery organic electro-optic materials and PIC designs.
- 112 Gbit/s PAM4 data transmission
- Driver-less operation at CMOS-compatible voltage swings below 0.5 V

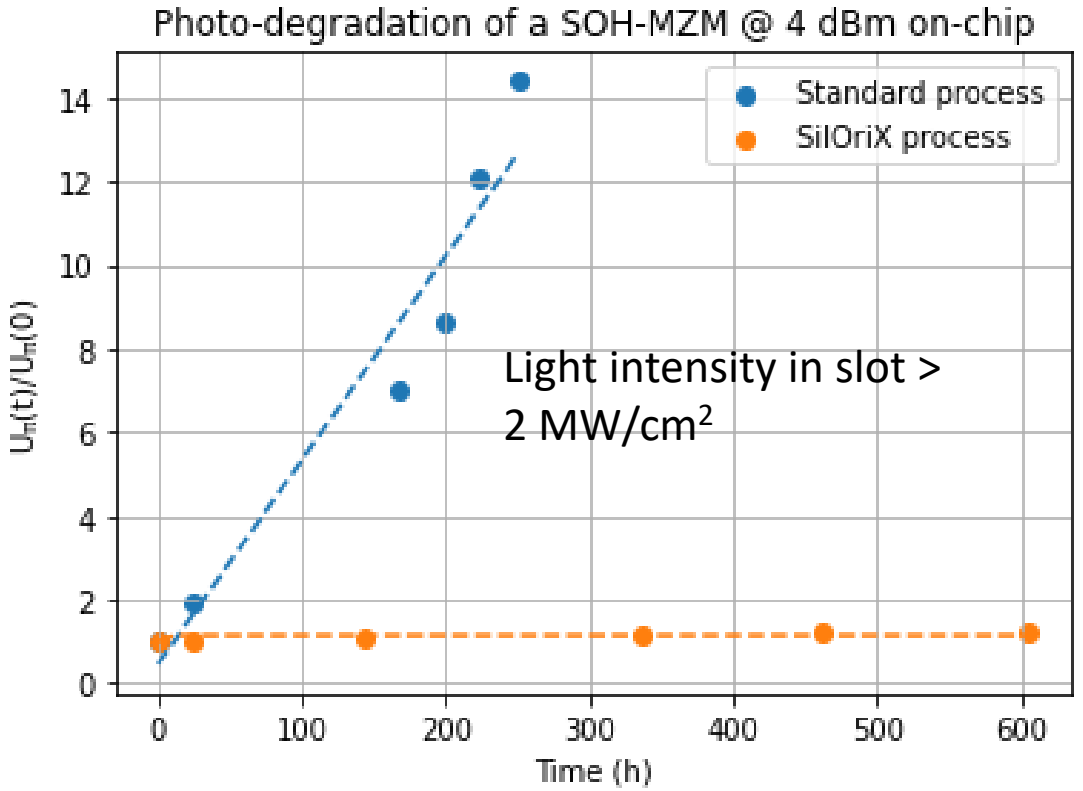
Long-term stable SOH modulators

Long-term stable SOH modulators



Long-term stable SOH modulators





Value chain and product development

SilOriX | Customers | Cooperation partners

Material synthesis
Synthesis of organic electro-optic materials

PIC Design
- Photonic and RF design
- Adaptation to foundry-specific processes
- Combination with IP blocks provided by customers

PIC Fabrication
Fabless, using existing silicon photonic foundry services

Hybridization
- Material formulation
- Deposition and encapsulation by wafer-level printing
- Wafer level poling
- Testing
- Dicing

Packaging and System Integration
- Mass products such as optical transceivers
- Major manufacturers of telecom and datacom equipment

Packaging
- Low-volume high-margin products
- Photonic and RF packaging (coop. with partners)

System Integration
Test and meas. equipment manufacturers

- Customized photonic integrated circuits (PIC) on a die level, for packaging and system integration by customers
- Customized packaged devices for high-margin niche applications
- PDK building blocks accessible through partner foundries
- Technology licensing for ultra-scale mass production by major transceiver manufacturers

In a nutshell

Silicon-organic hybrid electro-optic modulators with disruptive performance

Efficient

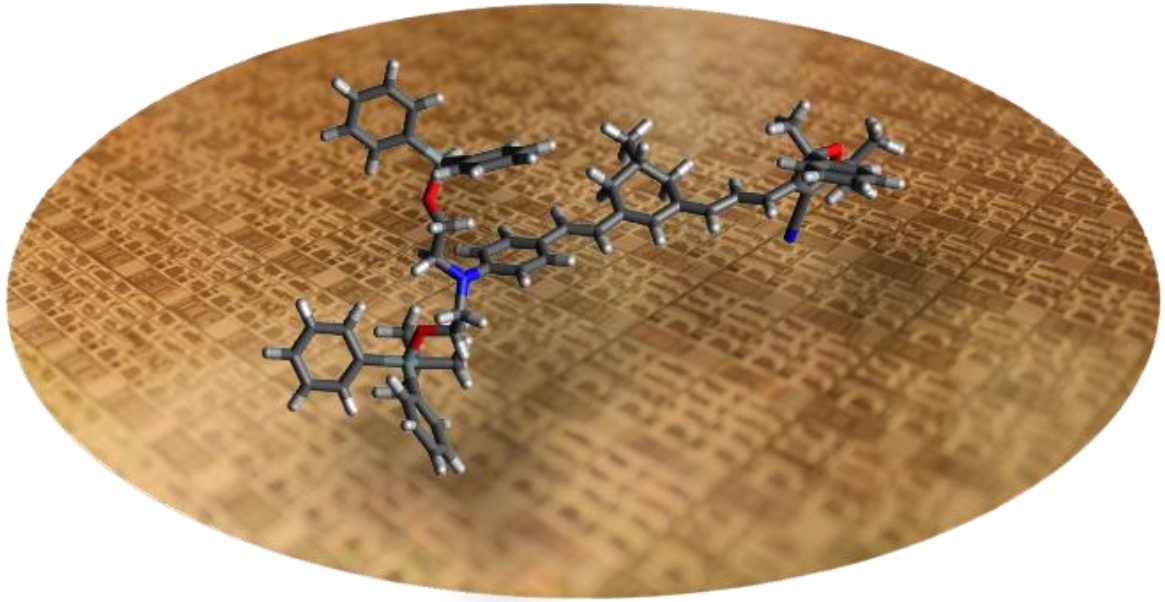
Sub-volt drive signals for ultra-low energy dissipation

Fast

Modulation at symbol rates of 190 GBd and beyond

Scalable

Monolithic back-end-of-line co-integration with established silicon photonics



www.silorix.com
info@silorix.com