Optical Link for Detector Instrumentation: In-Detector Multi-Wavelength Silicon Photonic Transmitter

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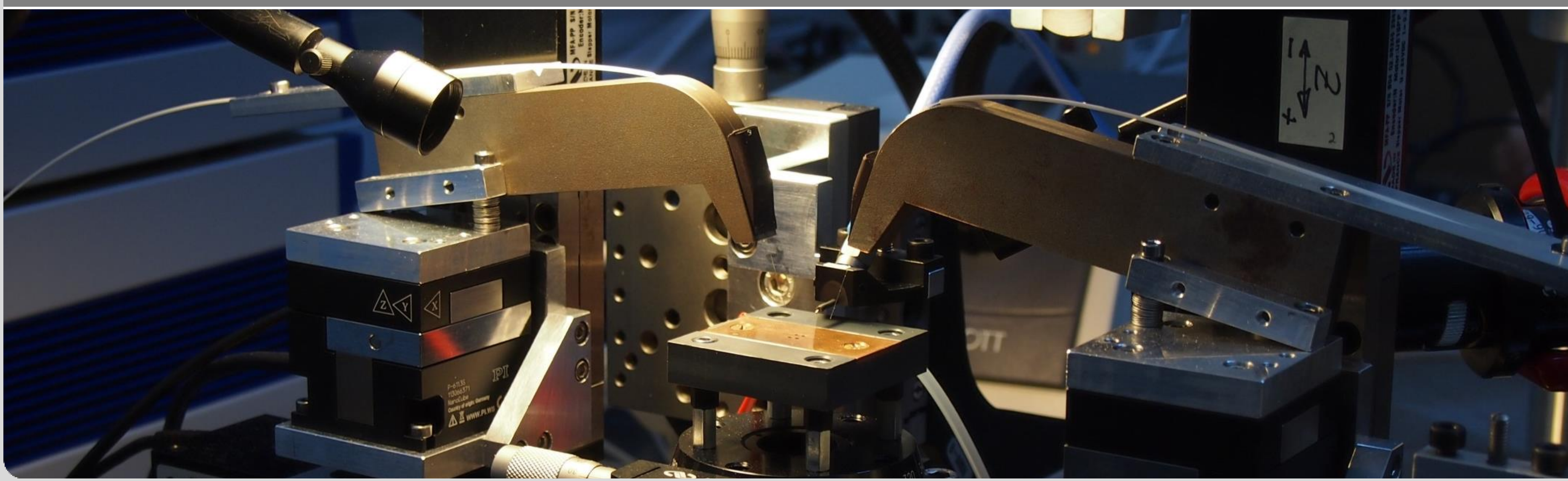
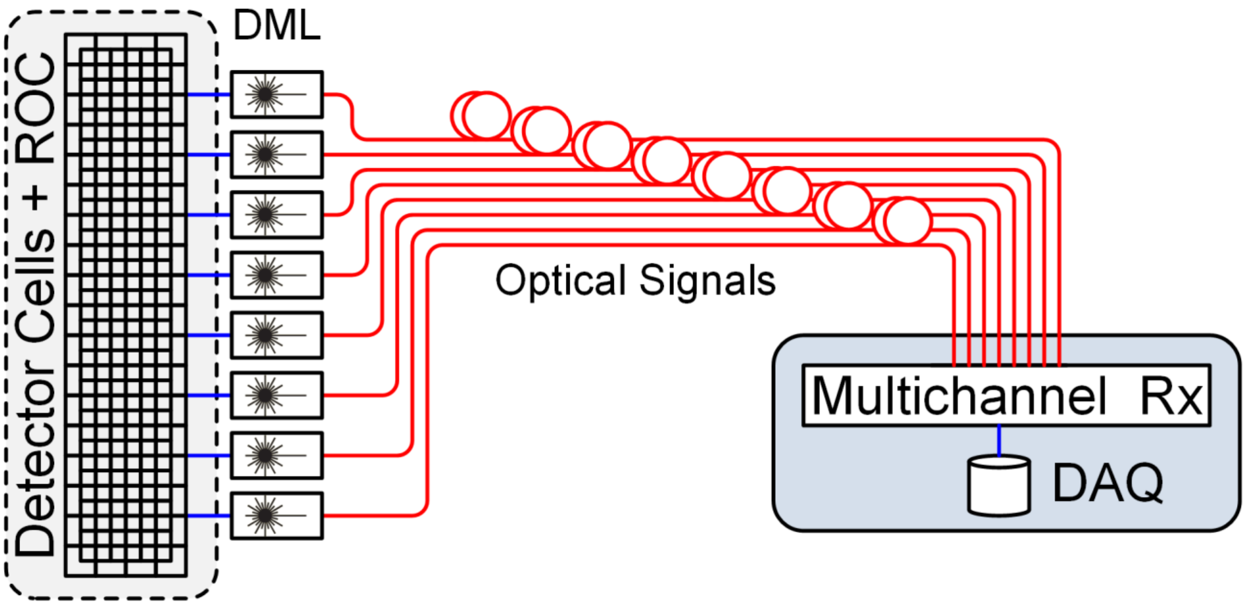
INSTITUTE FOR DATA PROCESSING AND ELECTRONICS (IPE)



Outline

- Introduction:
  Detector Data Readout System
- Components:
  On-detector Transmitter
- Application:
  Temperature Studies
- Packaging:
  Fiber-to-chip Coupling
- Conclusion

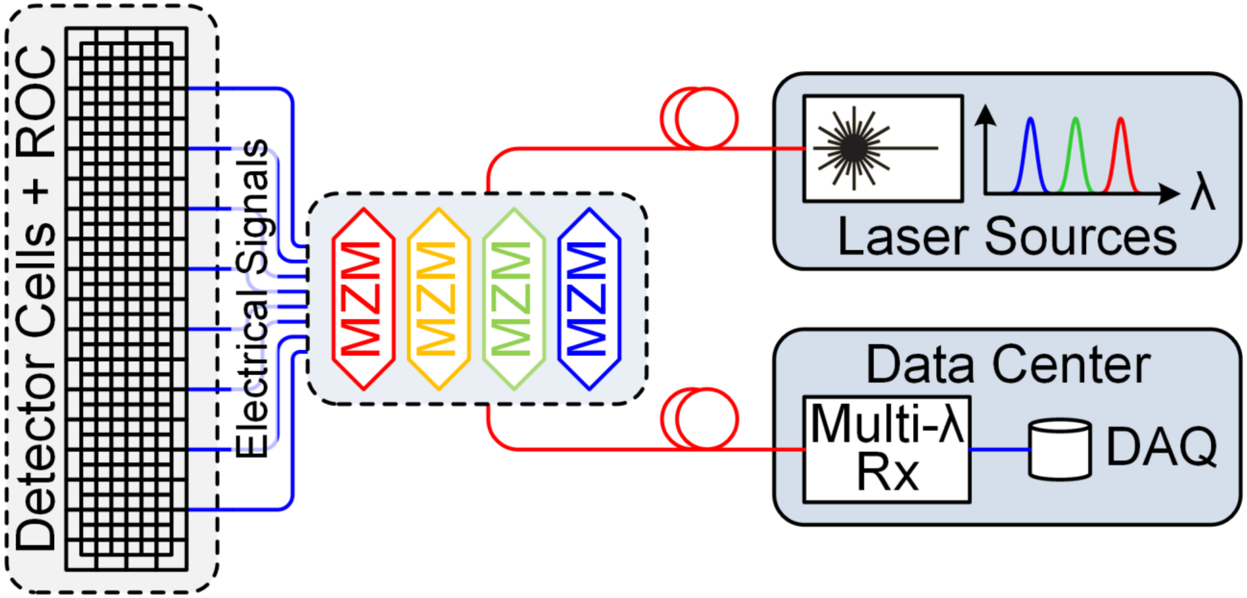
Detector Data Readout System



State-of-the-art

- Optical link for detector data readout
- Electrical signals from read-out chips (ROC) are encoded by **directly modulated laser diodes** (DML)
- One fiber per optical channel

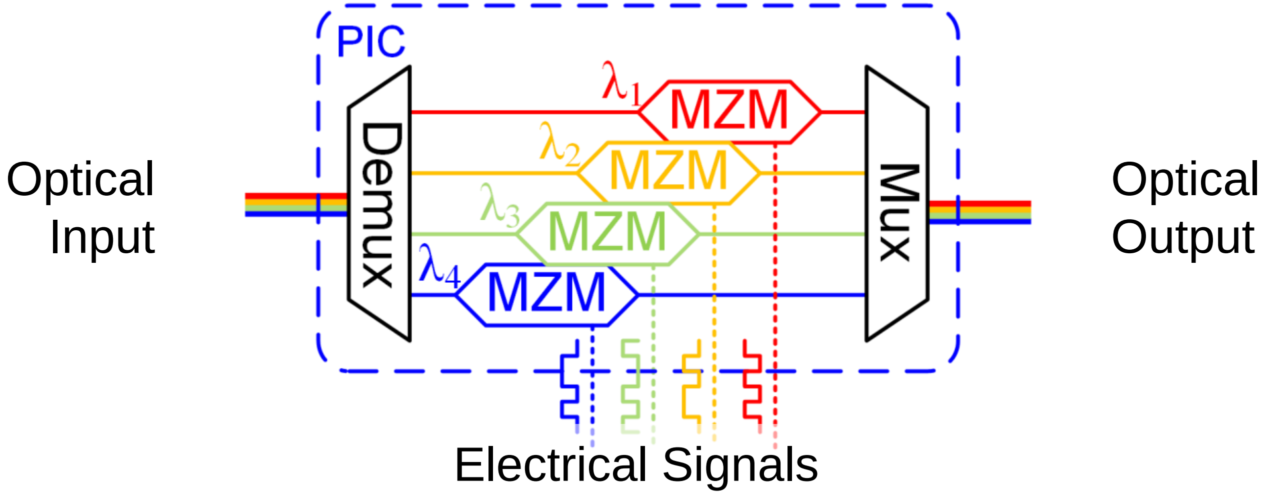
Next-generation Optical Data Transmission



The Vision

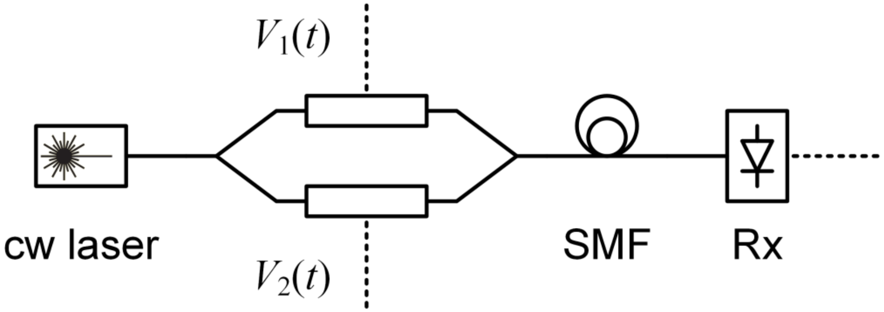
- Optical data transmission system based on wavelength division multiplexing (WDM)
- **Silicon photonics multi-λ Tx:** multiple monolithically integrated electro-optic modulators and optical (de-)multiplexers
- Lasers located off-detector

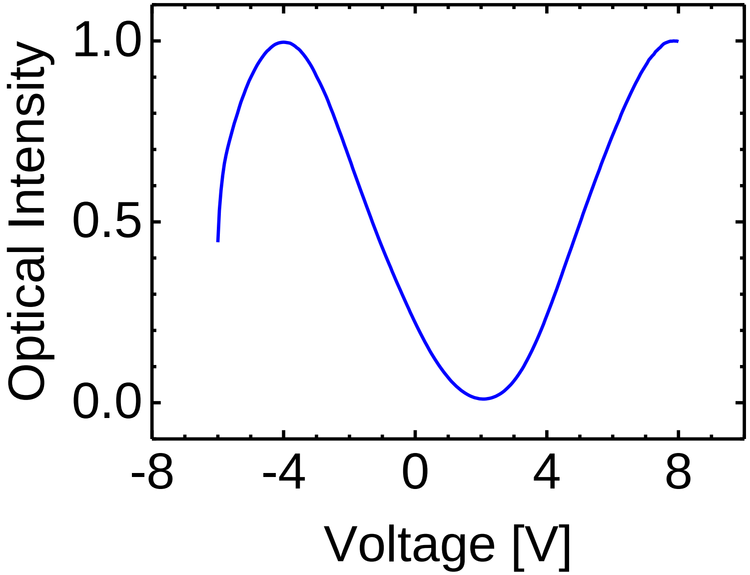
Multi-channel Transmitter



- Integration of Mach-Zehnder modulators (MZM) and (de-)multiplexers into single photonic integrated circuit (PIC)
- Incident optical carriers are demultiplexed and passed on to the respective modulator
- Each modulator encodes data onto the carrier
- All signals are multiplexed and transported over single fiber

The Mach-Zehnder Modulator

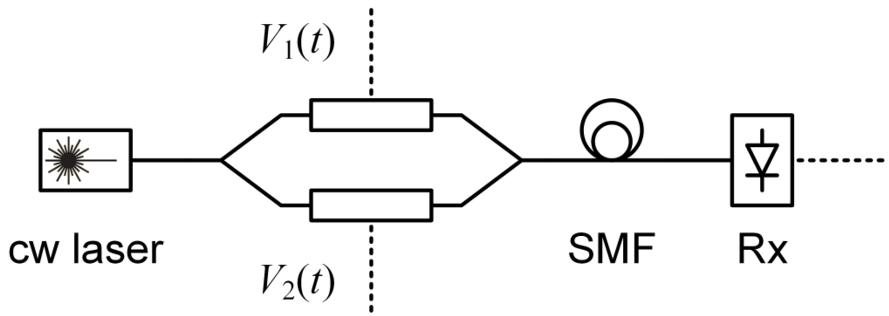


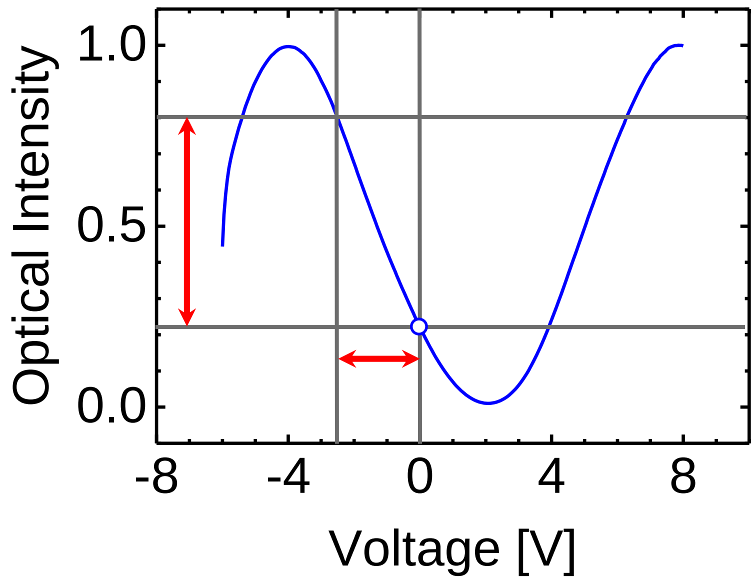


Data encoding onto optical carrier with Mach-Zehnder modulator

- Modulation of the optical field's phase in interferometer arms
- Change of refractive index due to electro-optic effect
- Superposition of signals at the output yields either constructive or destructive interference depending on the relative phase

The Mach-Zehnder Modulator





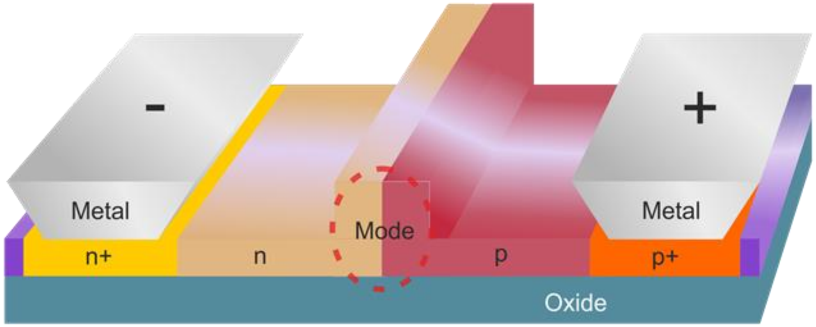
Data encoding onto optical carrier with Mach-Zehnder modulator

- Modulation of the optical field's phase in interferometer arms
- Change of refractive index due to electro-optic effect
- Superposition of signals at the output yields either constructive or destructive interference depending on the relative phase
- Driver voltage swing translates to change of optical intensity

Phase Shifters in Silicon Photonics

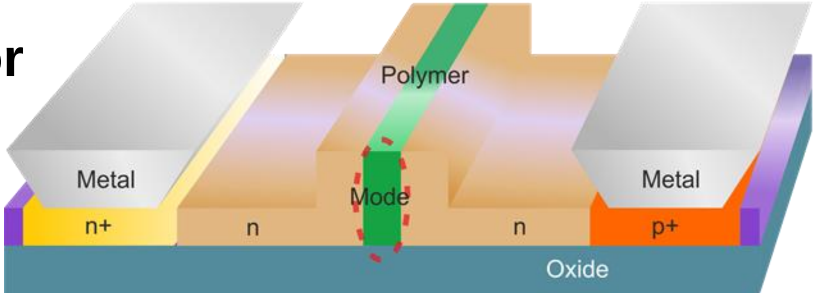
Depletion-type pn modulator

Refractive index change by free carrier depletion in the waveguide

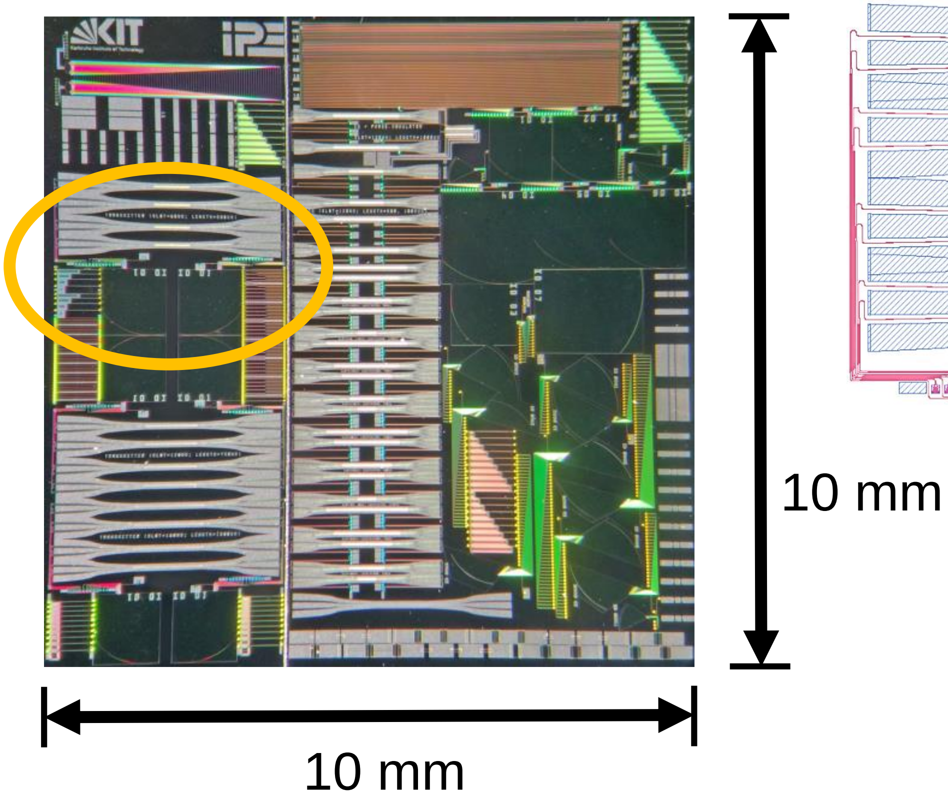


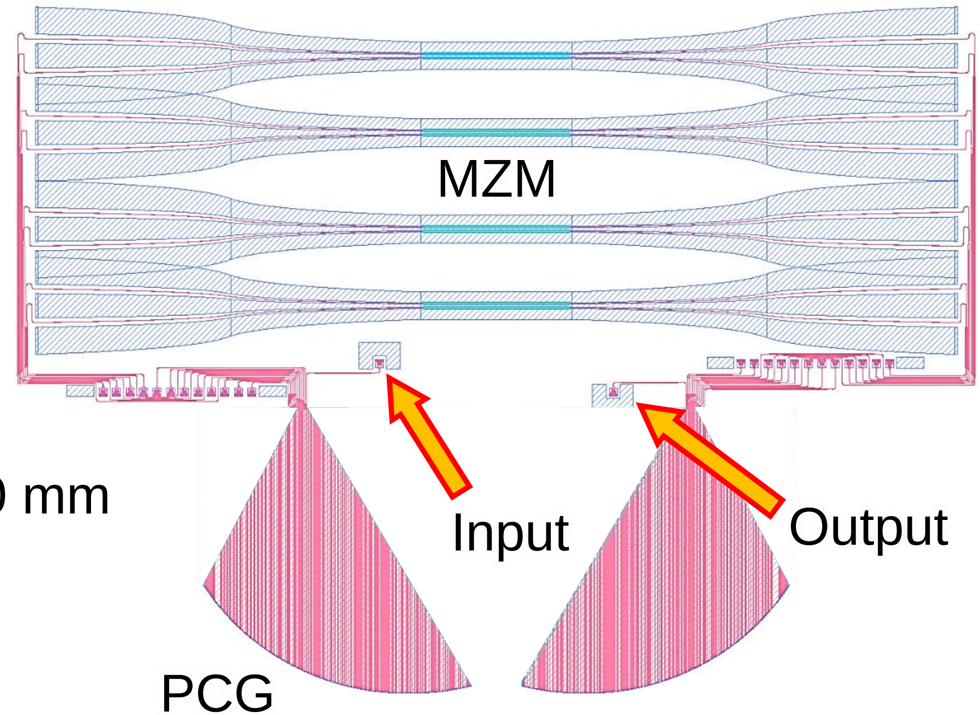
Silicon-organic hybrid (SOH) modulator

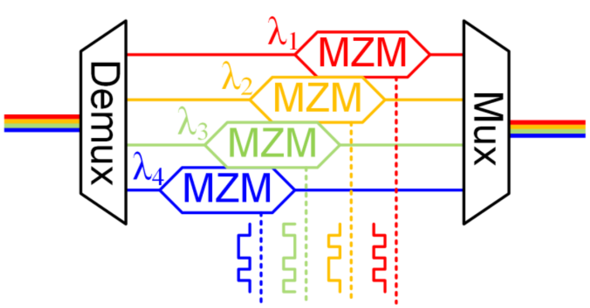
Passive silicon slot waveguide filled with an electro-optic polymer



Integrated 4-Channel Transmitter



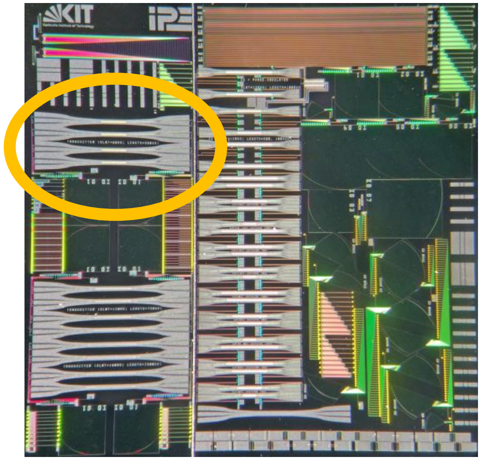


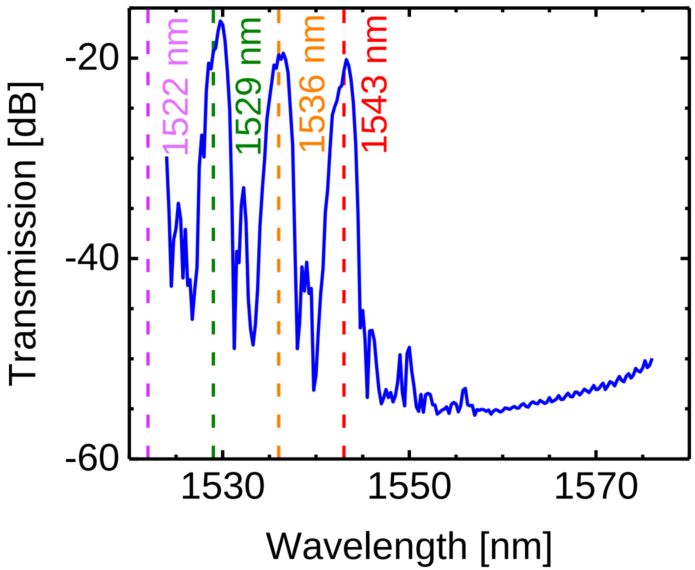


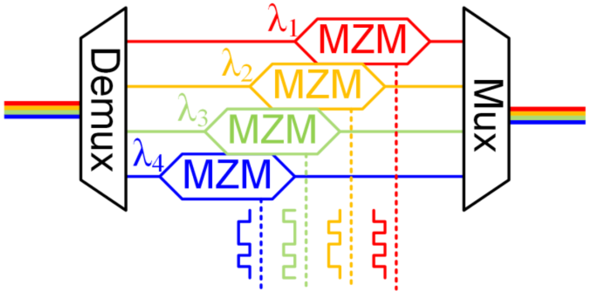
- MZM: silicon-organic hybrid (SOH) technology
- (De-)Mux: planar concave gratings (PCG)
- Fabrication: **IMS CHIPS** (Stuttgart)

Integrated 4-Channel Transmitter

(De-)Mux	Bandwidth	2 nm
	Suppression	>25 dB

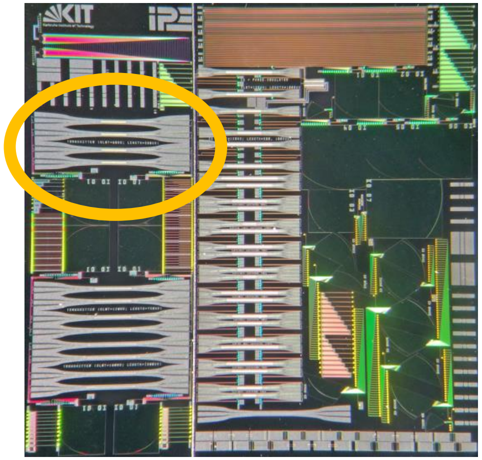


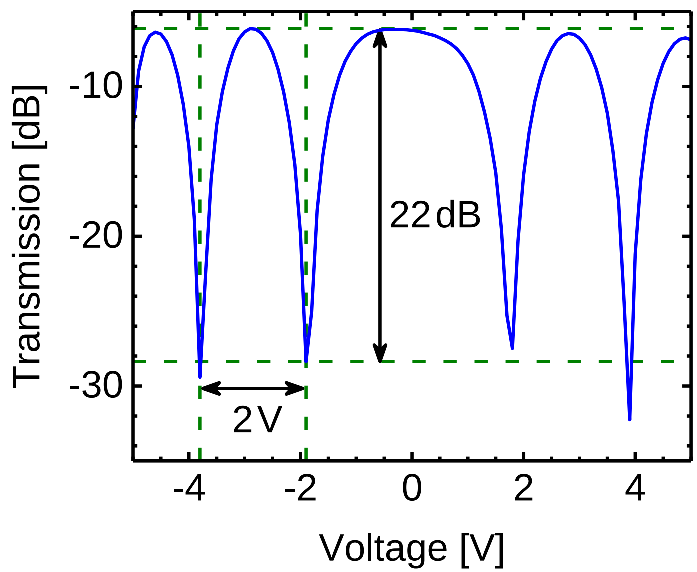


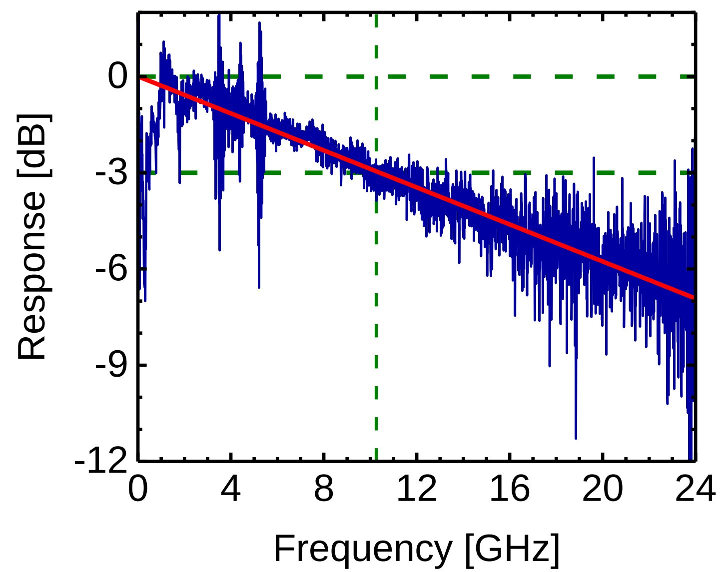


Integrated 4-Channel Transmitter

(De-)Mux	Bandwidth	2 nm
	Suppression	>25 dB
Modulators	Extinction Ratio	22 dB
	π Shift Voltage	1 V
	3 dB Bandwidth	10 GHz







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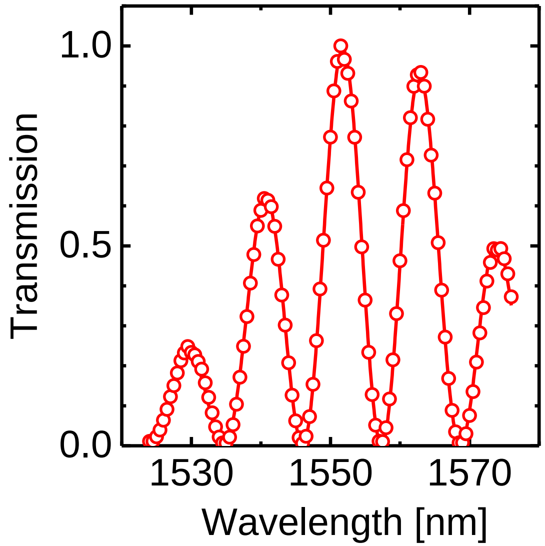
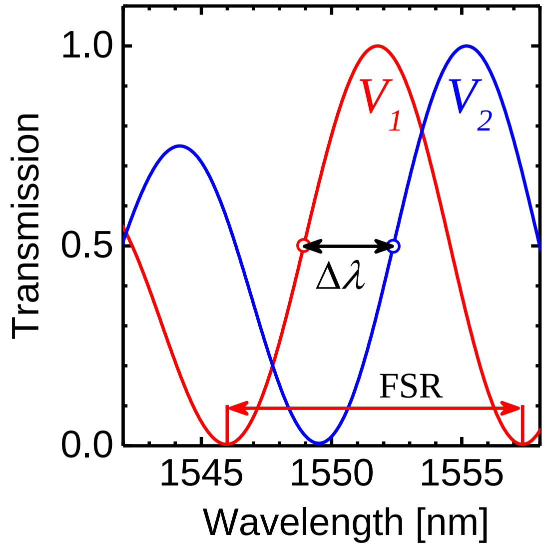
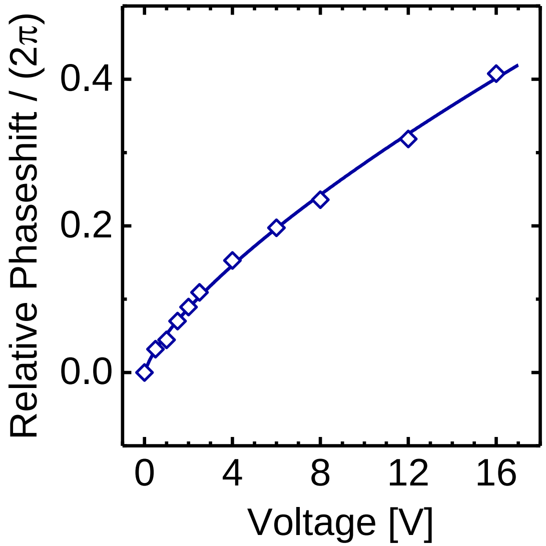
MZM Modulation Efficiency

- Measurement of asymmetric MZM transmission spectrum
- Shift of spectrum by $\Delta\lambda$ when applying a voltage V_i
- Total phase cycle: free spectral range (FSR)
- Modulation efficiency: relative phase shift $\Delta\lambda$ / FSR







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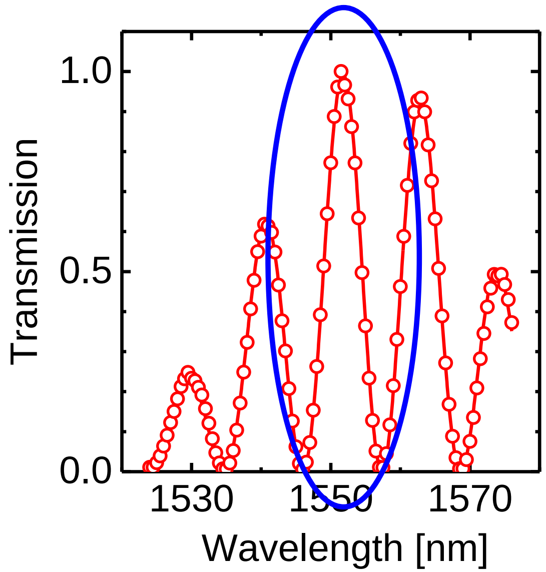
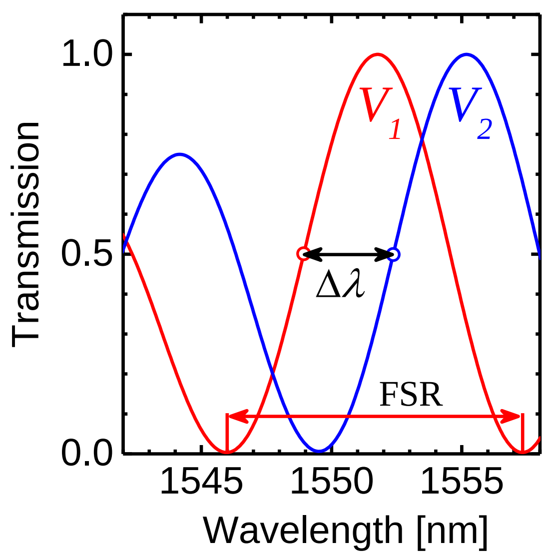
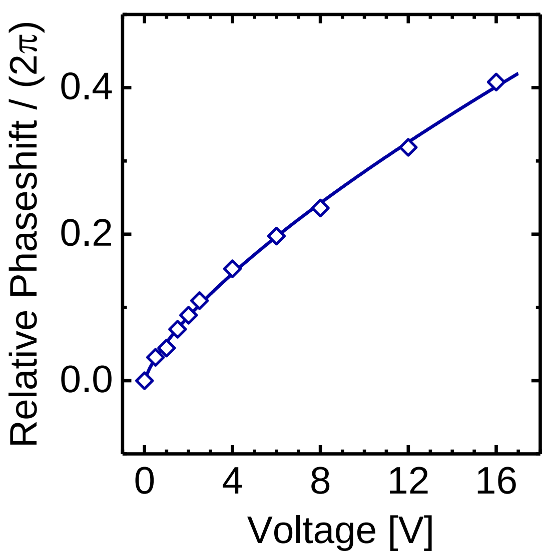
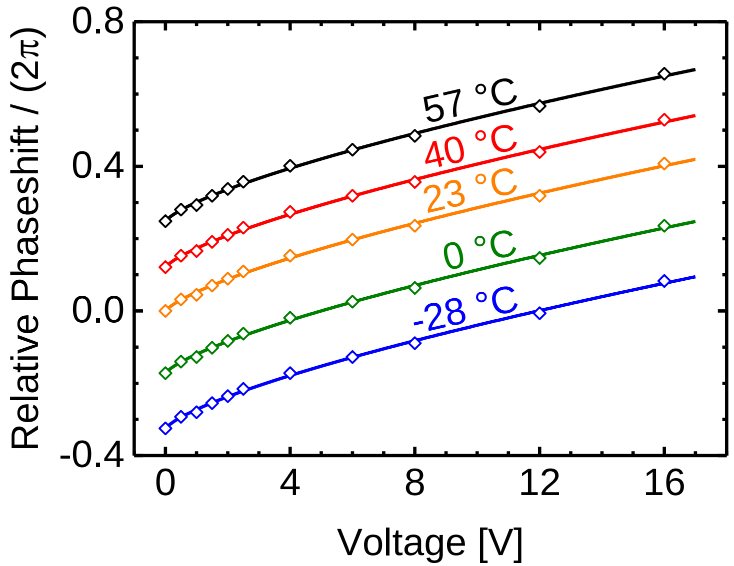


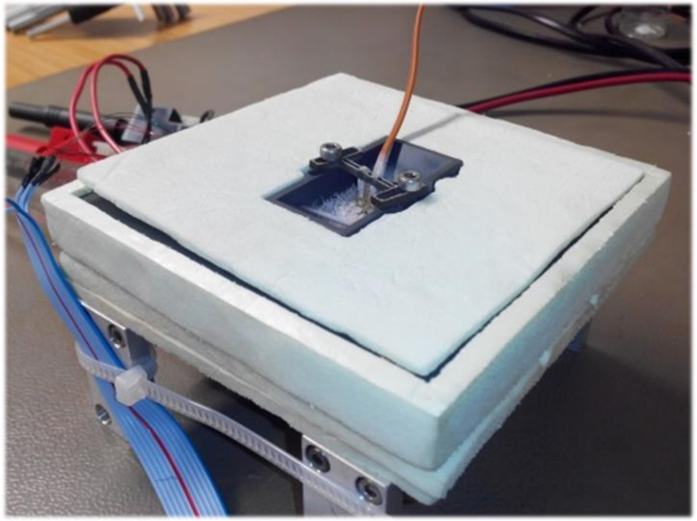


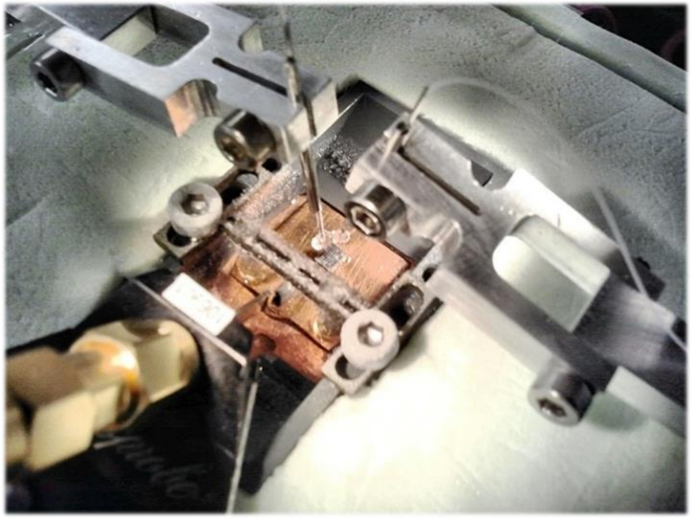


Temperature Studies: pn-Modulator

- Temperature shift induces constant phase offset < 0.05 K^{-1}
- Modulation characteristic is **not affected**
- Wavelength shift can compensate for operating point offset

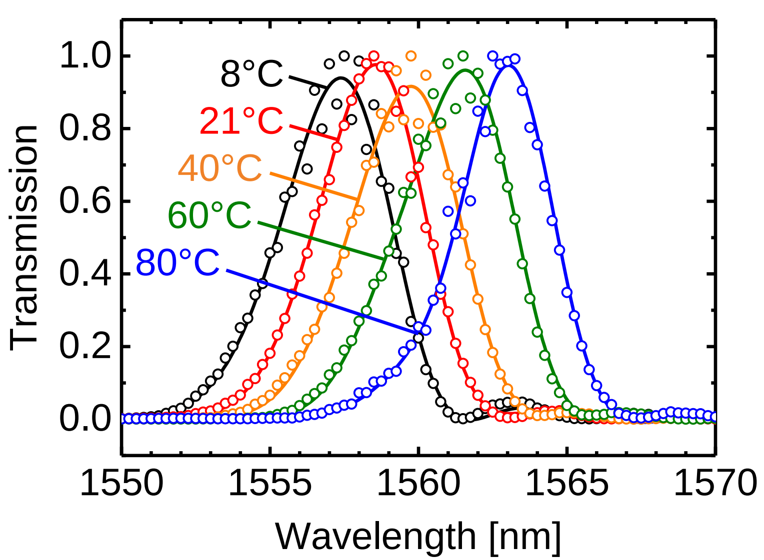


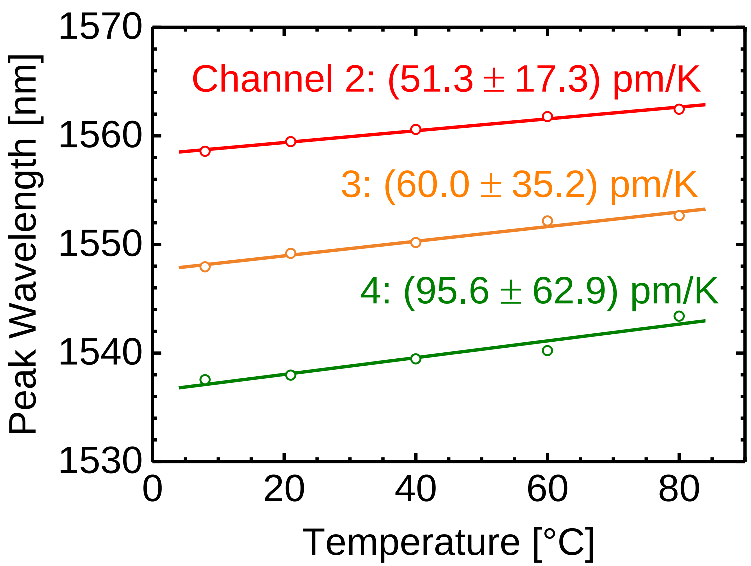




PCG: Temperature Studies

- Channel separation by means of diffraction
- Refractive index changes with temperature
- **Linear shift** of filter transmission window < 100 pm K^{-1} manageable if bandwidth is chosen accordingly





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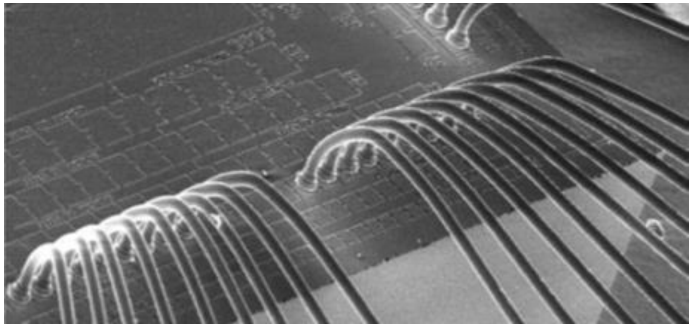
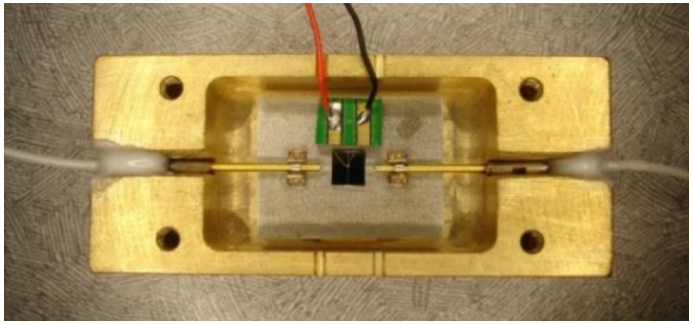
Package Design Considerations

Electrical connection
Wire bonding
Impedance matching circuit

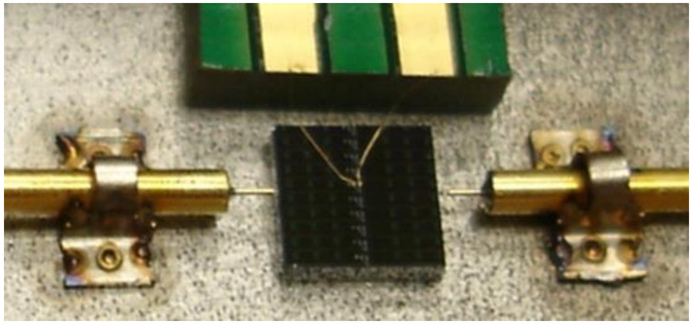


T. Tekin, *IEEE J. Sel. Topics Quantum Electron.* **17**, 704 (2011)

Housing
Device or application
Operating conditions and footprint



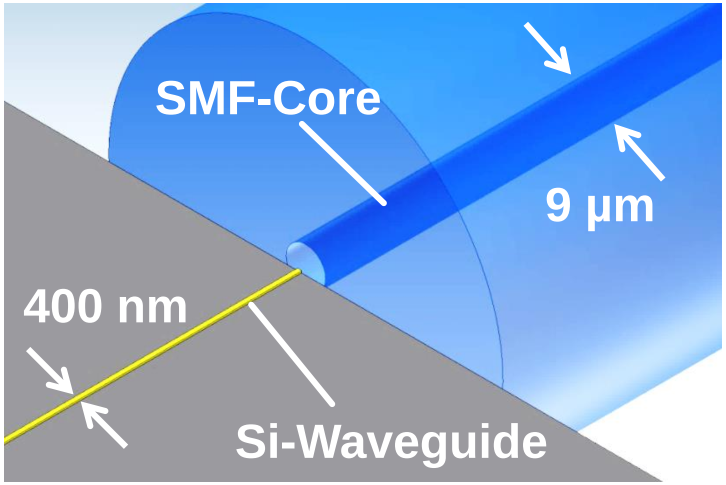
Fiber-to-chip coupling
Active or passive alignment
Fixation of fibers

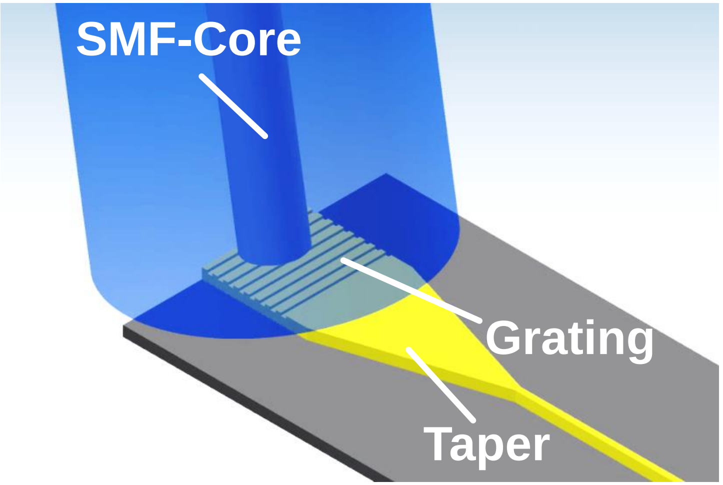


J. Song et al., *Opt. Express* **19**, 18020 (2011)

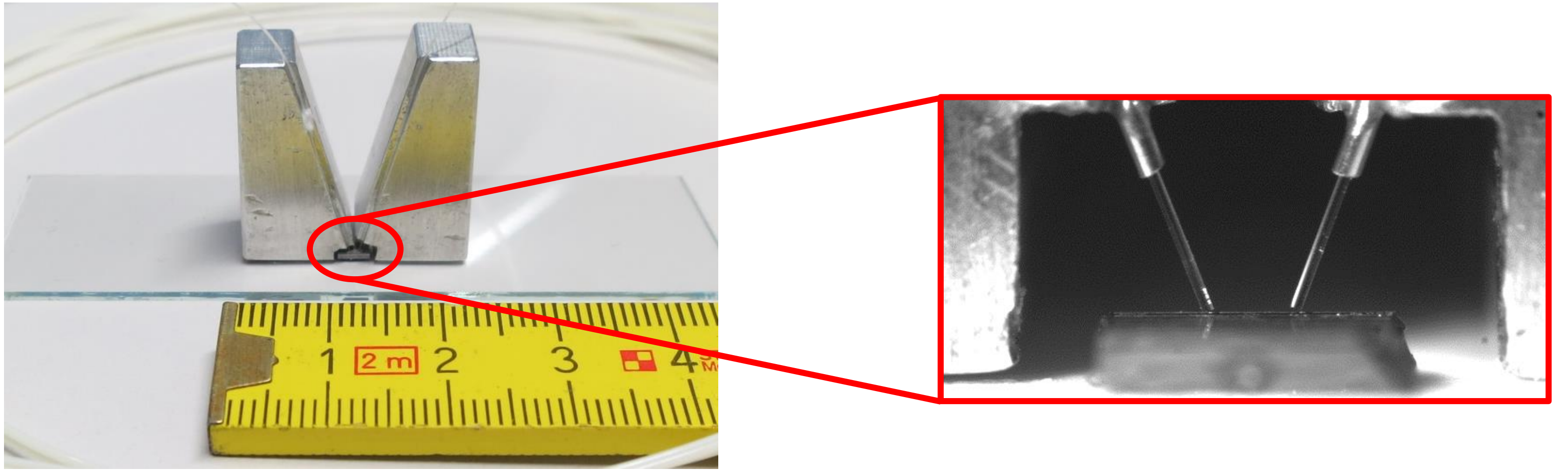
Coupling SMF to Si-PIC

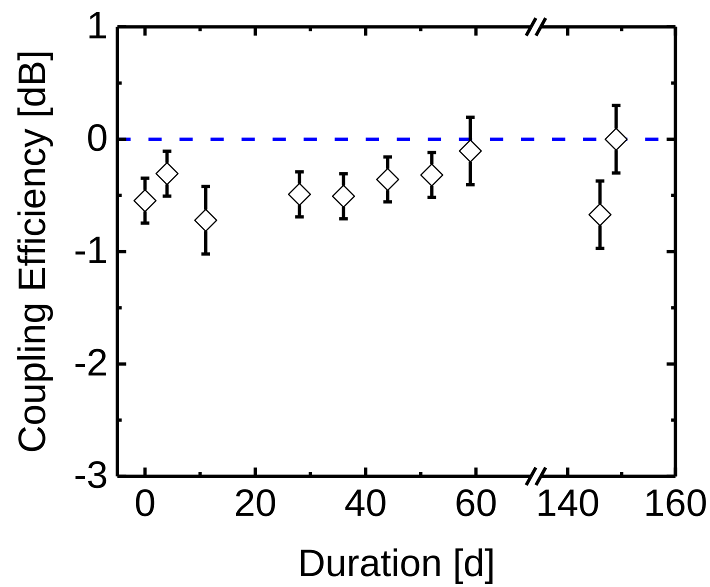
- Mismatch between Si-waveguide and fiber modes
- Edge Coupling
  - Dicing and polishing of chip edges
  - Small alignment tolerance: ± 0.5 µm
- Surface Coupling
  - Grating couplers: coupling anywhere on the chip
  - Alignment tolerance improvement: ± 2.5 µm





Development of Coupling Process

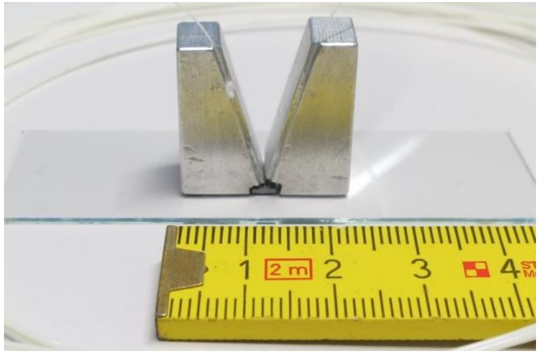


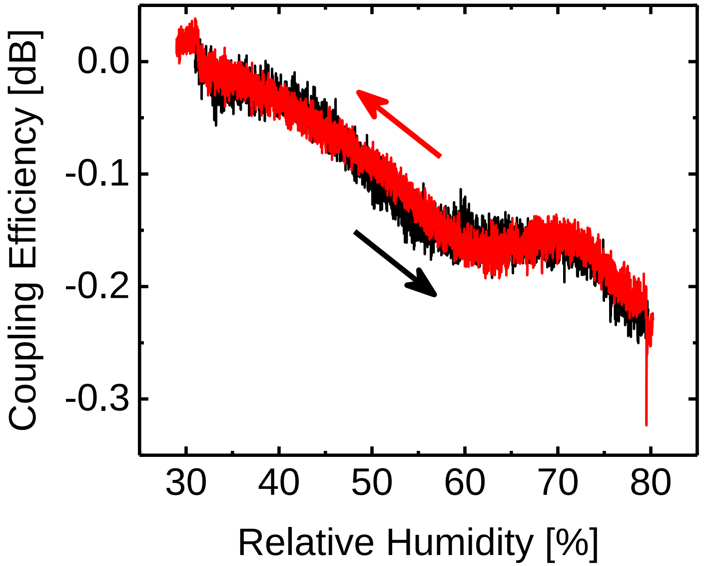


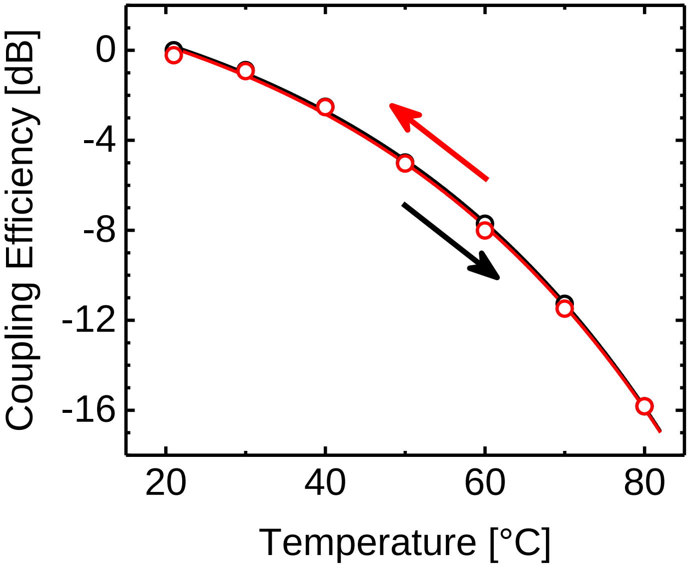
- Surface coupling design with fibers on aluminum sockets
- Micrometer precision alignment
- Fixation of fibers and sockets with UV-curing adhesives
- No significant loss over more than **5 months**

Stability of Fiber-to-chip Coupling

- Coupling efficiency weakly dependent on relative humidity
- Change in temperature: strong loss due to thermal expansion of sockets
- Both effects reversible



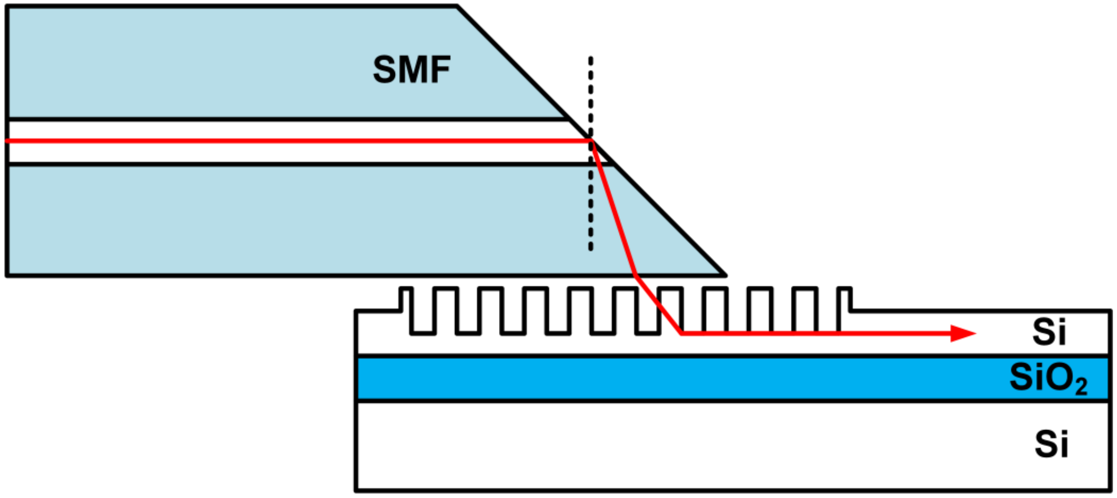




In-plane Fiber-to-chip Coupling

Angle-polished fibers

- Surface coupling with planar alignment
- Polishing of fiber facet
- Total internal reflection



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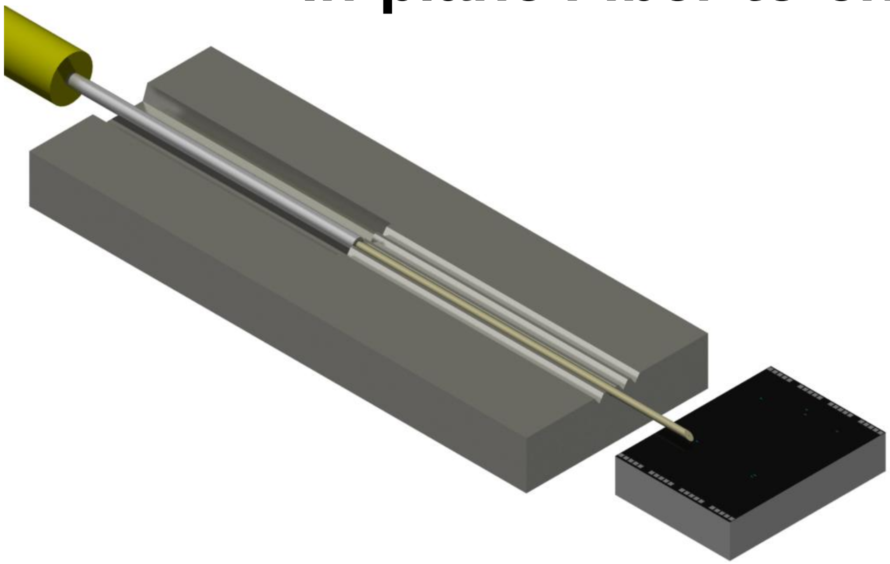
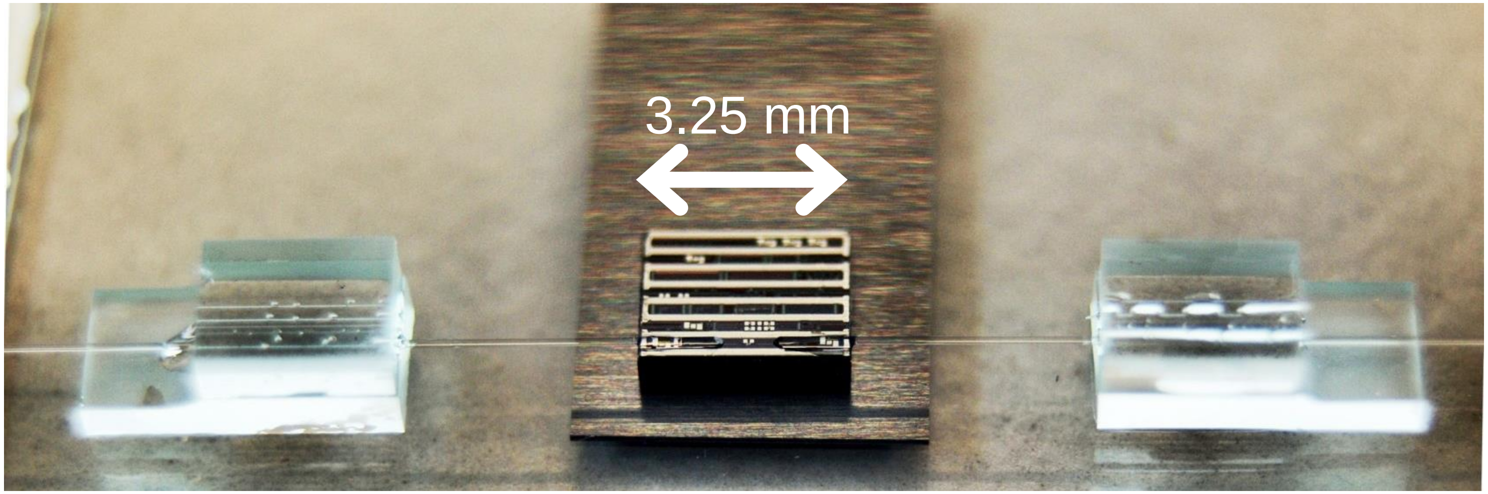
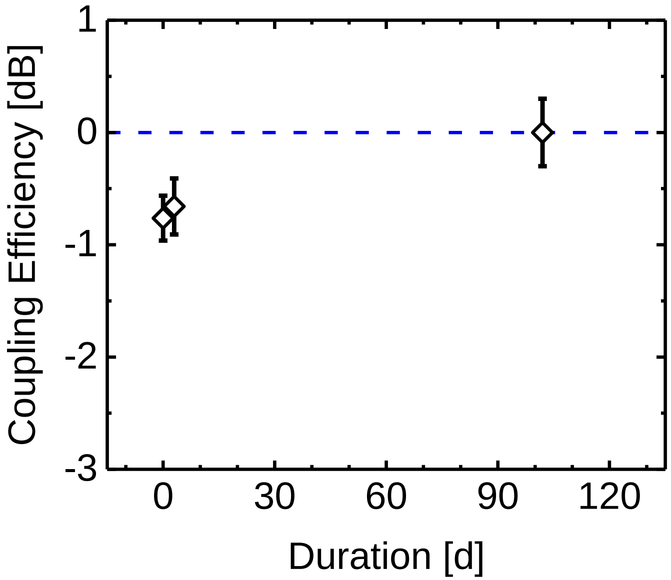
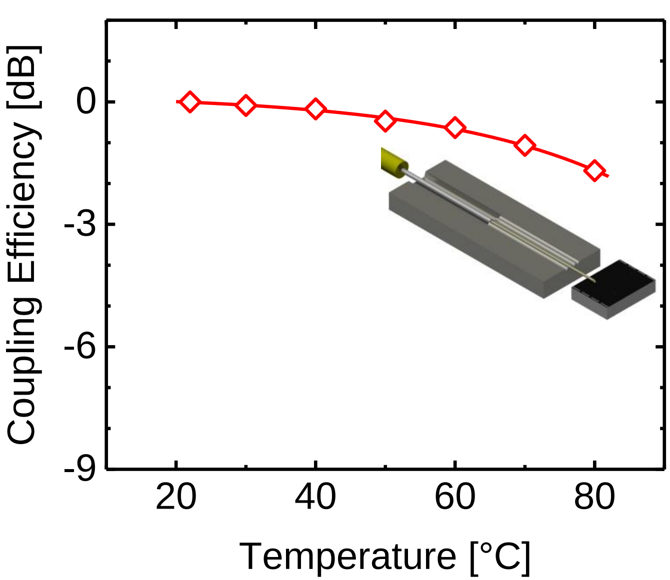


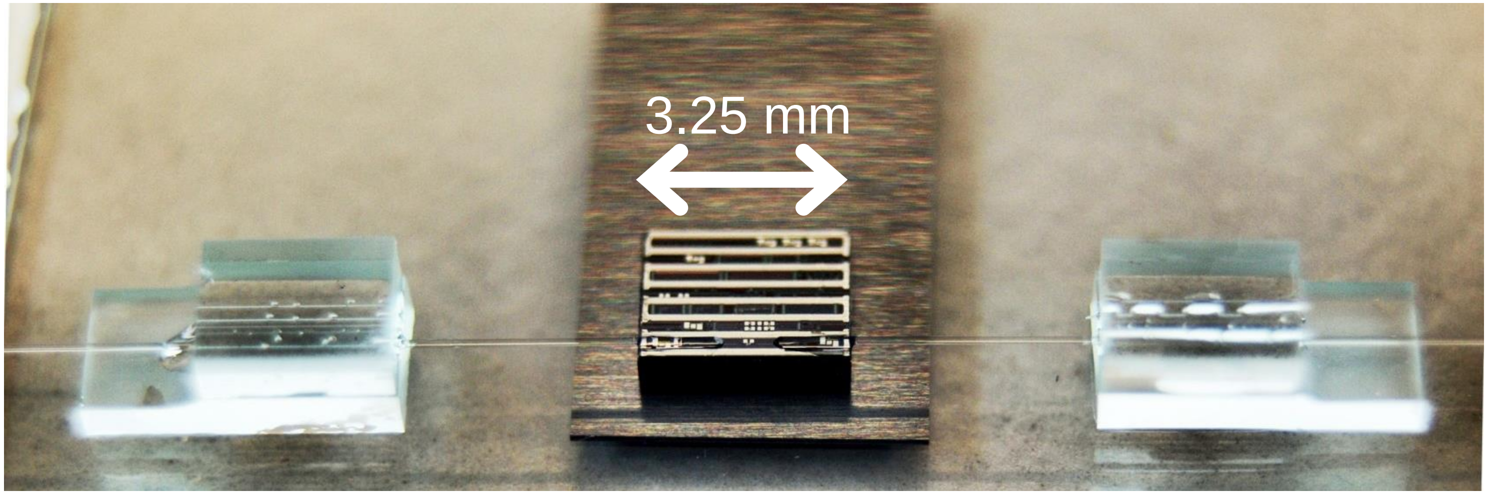
- Substantial reduction of spatial requirements
- No power penalty
- No stability impairments



In-plane Fiber-to-chip Coupling







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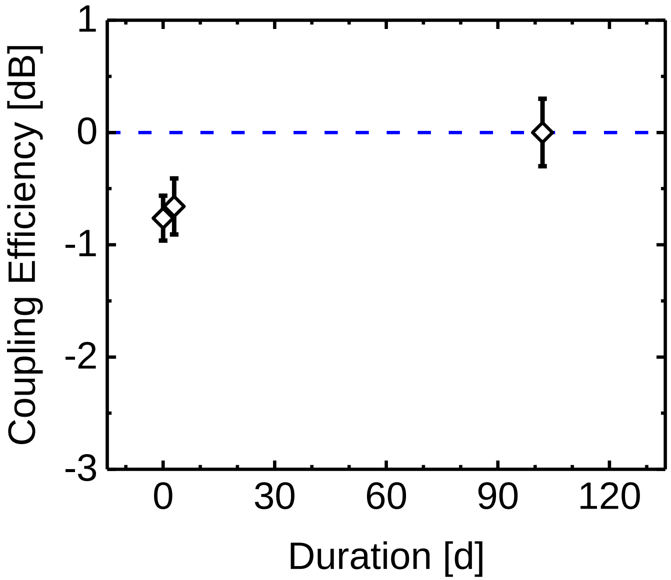
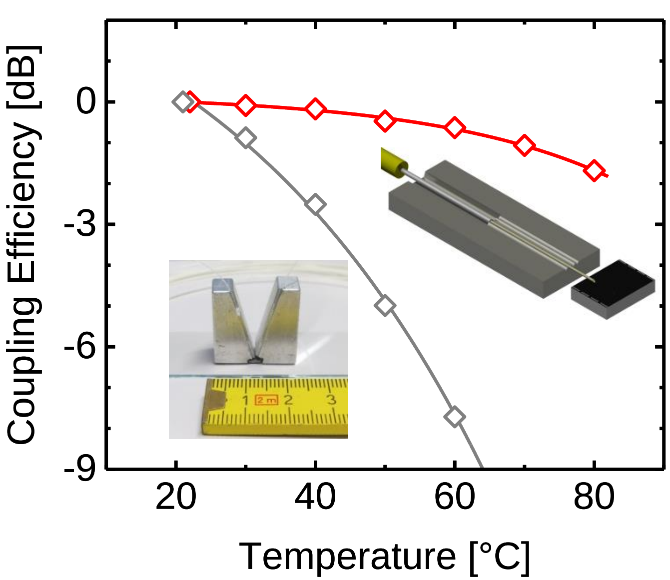
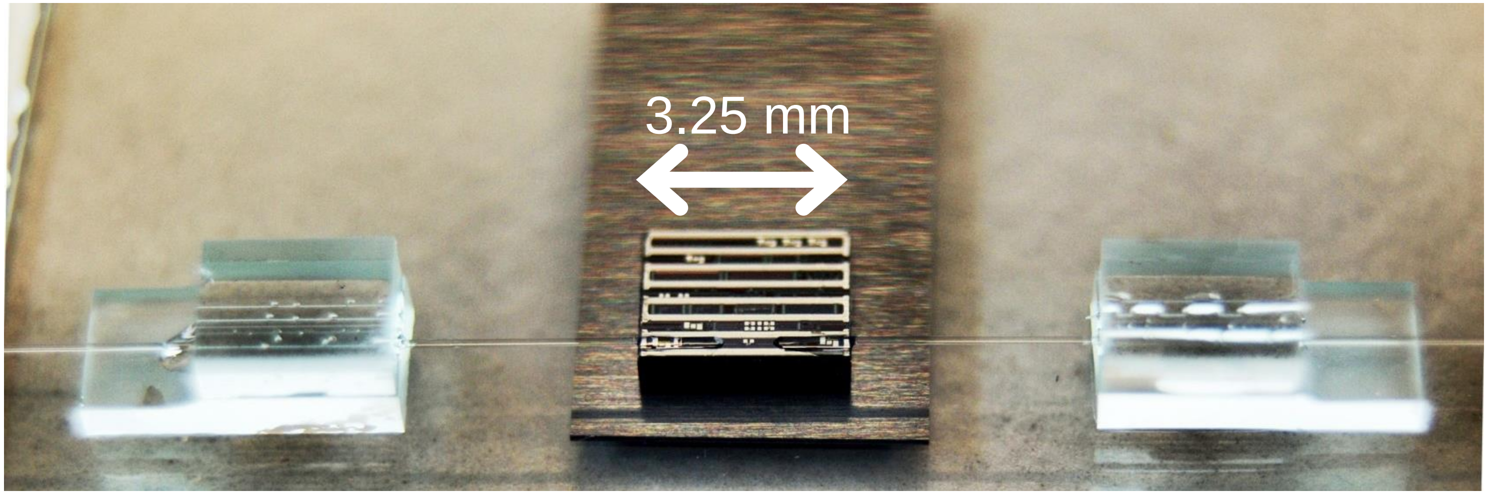


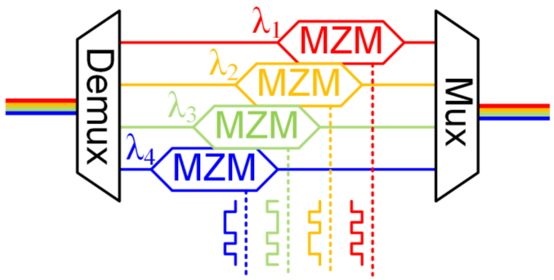




Conclusion

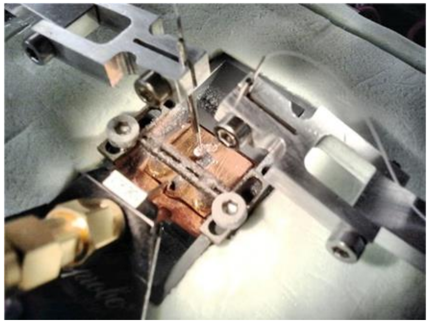
On-detector **4-channel optical transmitter**

- Monolithic integration of modulators and (de-)mux
- Total data rate ≥ 4·10 Gbit/s becomes feasible
- 22 dB extinction ratio @ 1 V swing



Temperature studies on transmitter components

- Mach-Zehnder modulators: phase offset < 0.05 K^{-1}
- PCG (de-)mux: transmission window shift < 100 pm K^{-1}



Advances in **packaging process**

- In- /off-plane surface fiber-to-chip coupling alignment
- Dependency on environmental conditions minimized
- Long-term stable