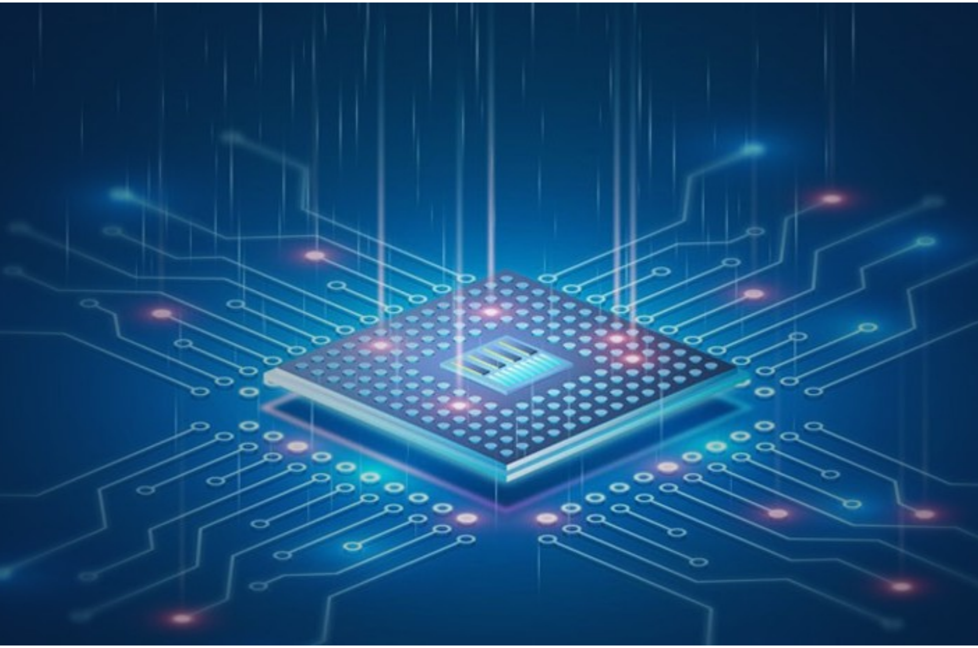
Fibre to the Pixel

Towards an all-optical data transmission for pixel detectors



2023/05/17

Branislav Ristić

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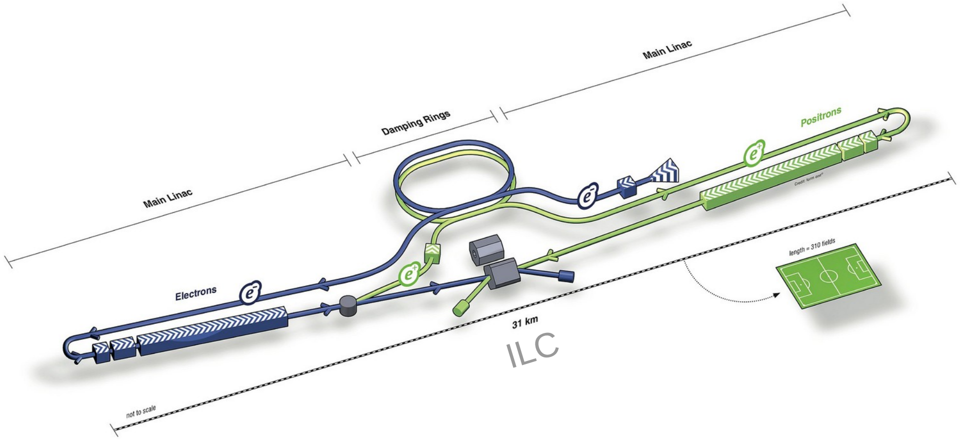
Next-generation colliders



Standard Model: A success story, but incomplete

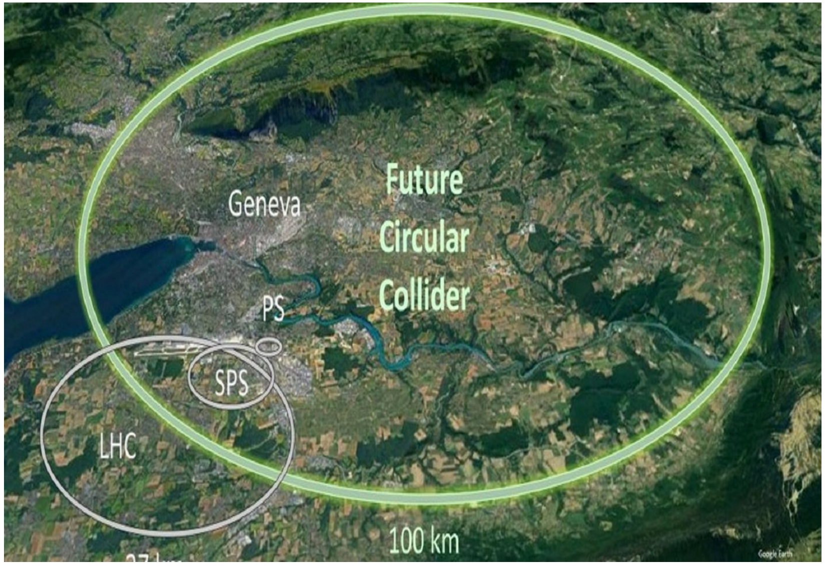
- Dark Matter, neutrino mass, CP violation ...

Physics goals for post-LHC Lepton Colliders:

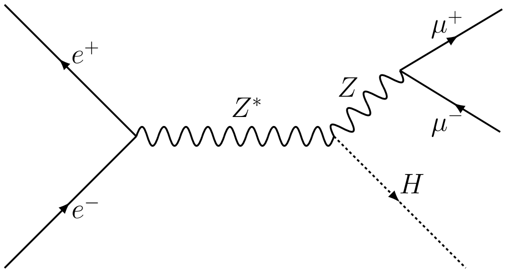
- Higgs/Z Factory
  - Precision measurements of Higgs, EW, heavy quarks
- Indirect BSM searches

Excellent tracking performance needed

- Flavour tagging: c, b
- Precise measurement of leptonic final states



Next-generation colliders



$e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^- X$

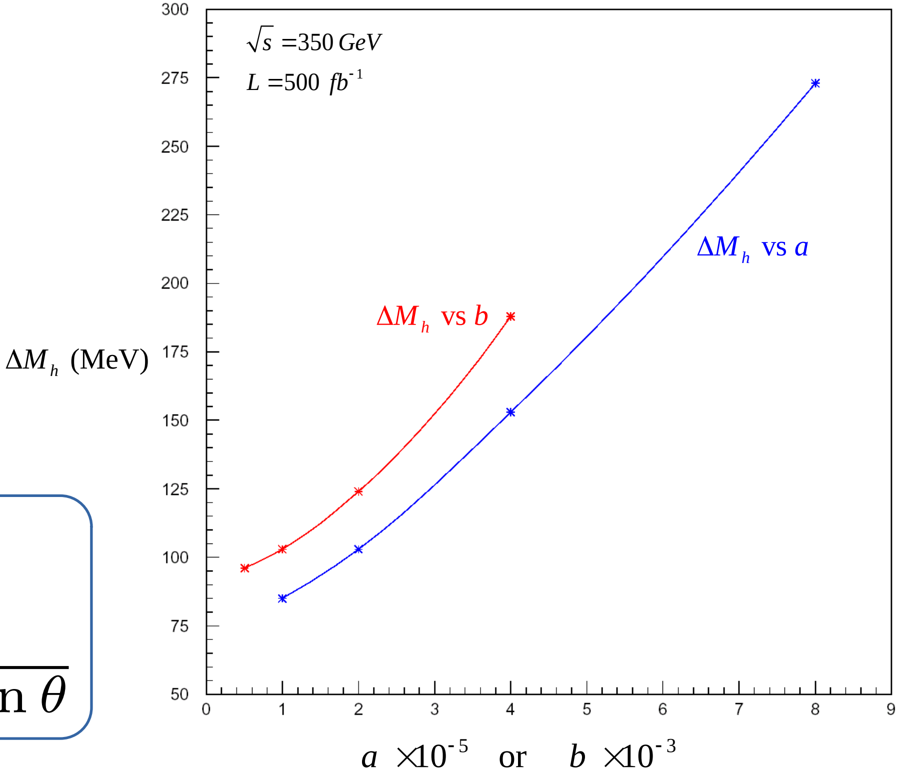
Challenges for trackers

- No pile-up and less radiation
- Material budget < 0.5% X/X_0
  - ➔ Power consumption and cooling
- High pointing resolution of few µm
  - ➔ Fine granularity
  - ➔ Multiple scattering
- Trigger-less readout
  - ➔ Close to no buffering

➔ High readout bandwidth

Resolution — Material budget

$$\frac{\delta p_t}{p_t^2} = a \oplus \frac{b}{p_t \sin\theta}$$



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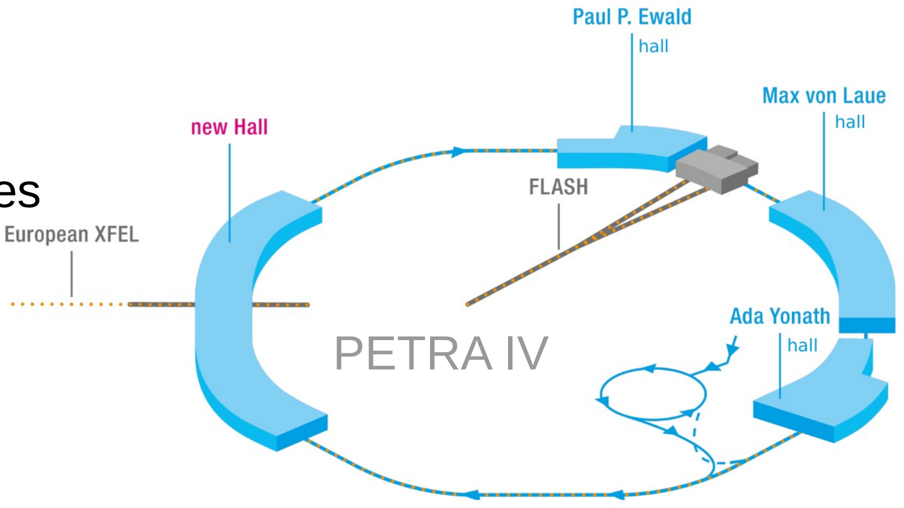
Fourth generation light sources

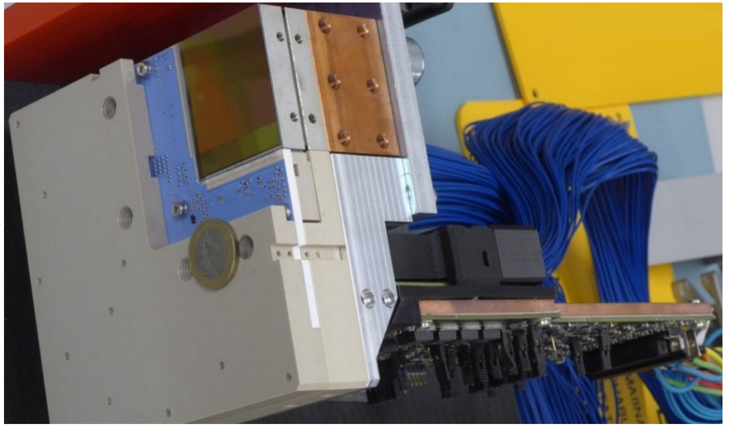
Advances in photon science

- Novel materials and quantum technologies
- Real-time recording of chem./biol. processes
- ➔ Nanoscale resolution X-ray imaging
- ➔ High-speed photography



Novel detectors

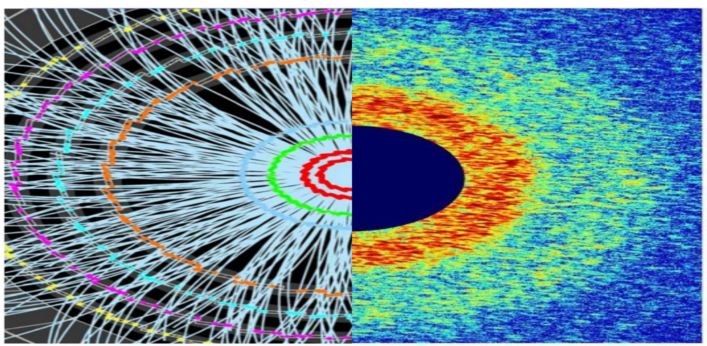
- High-granularity detectors (<30um pixel size)
- 100 kHz full-frame readout
- Large dynamic range
- Precise time of arrival of single photons

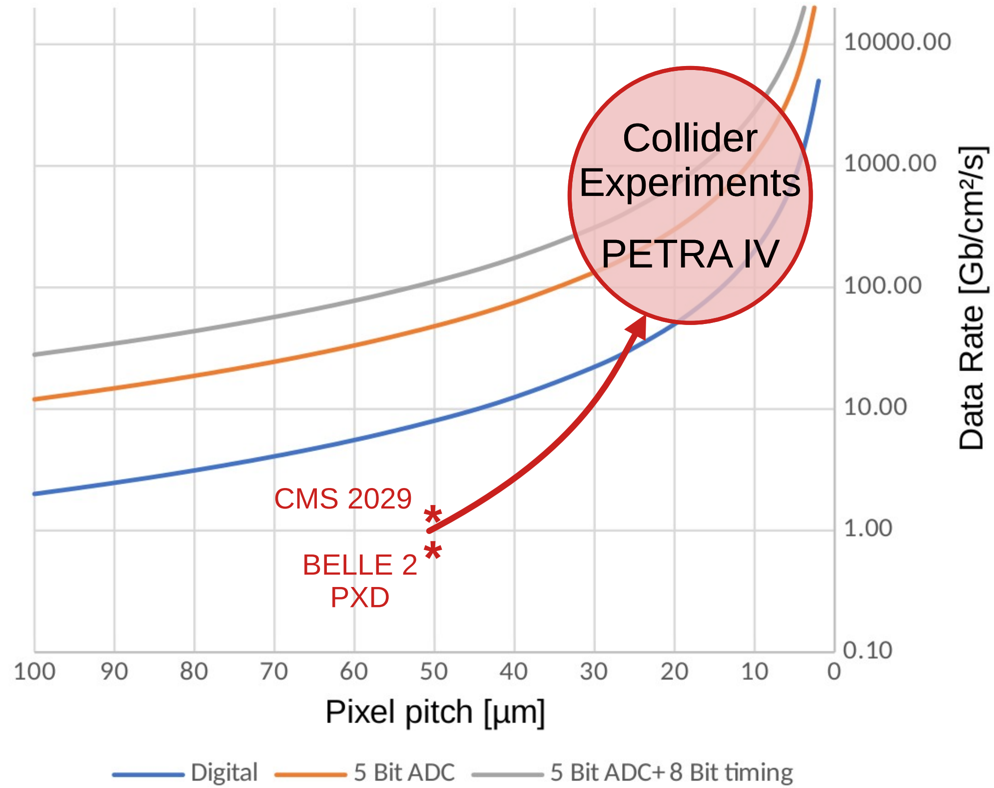


Next-generation imaging and particle detection

Challenges for modern detectors

- Extreme data-rates
  - High resolution and frequency
  - Increase by orders of magnitude
- Significant power densities
- Limitation on material and services
- Miniaturisation





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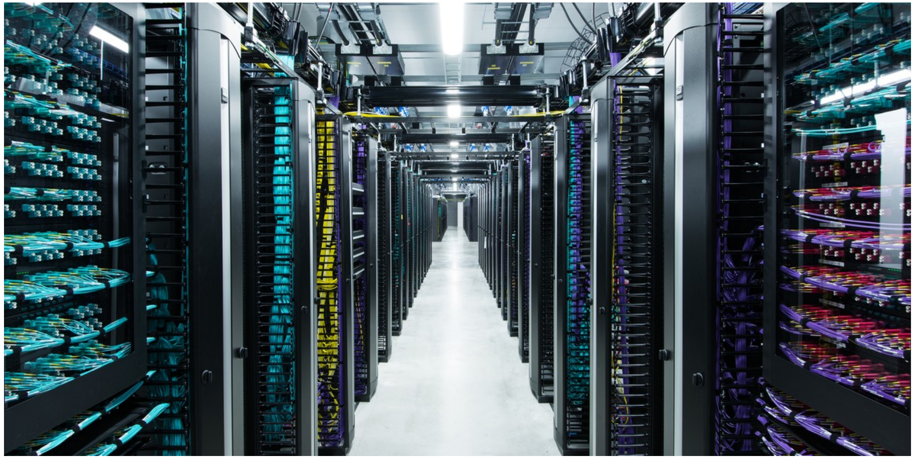
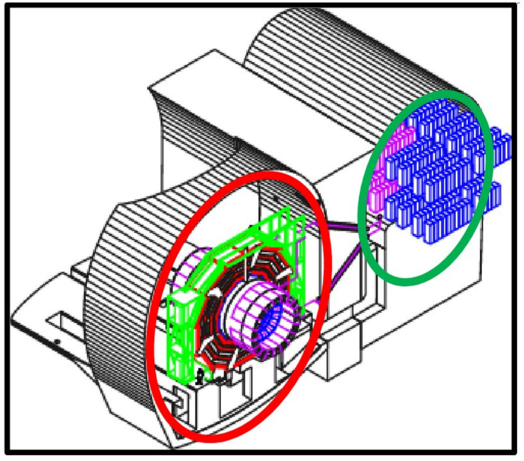
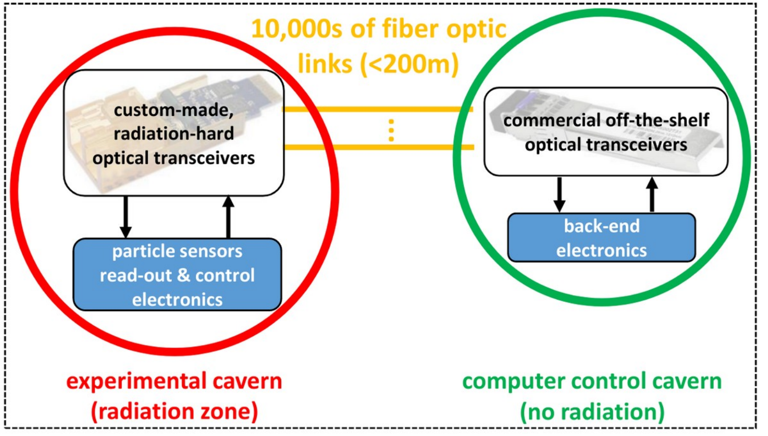
Optical data transmission

- Common in data centres
  - Link bandwidths up to several 100Gbps
  - Low power and light-weight
  - Immune against EM interference

➔ Use in HEP experiments
  - Detector to back-end transmission
  - High-speed ↔ Power ↔ Radiation







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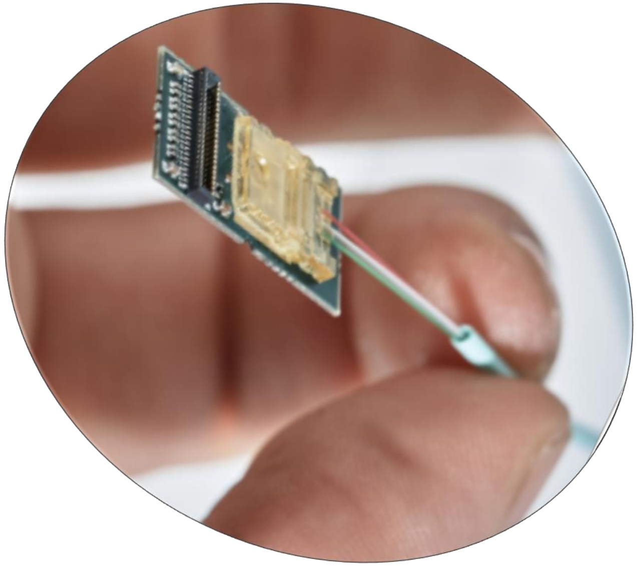
State of the art in HEP: The Versatile Transceiver+

- Dedicated electro-optical converter
- Modification of commercial technology
  - Vertical-Cavity Surface-Emitting Laser
  - PIN diode receiver
  - Both GaAs based
- Direct modulation of laser amplitude
- 10Gb/s uplink, 2.5Gb/s downlink
- Moderately radiation tolerant
  - Up to 1 MGy TID and $1 \times 10^{15} n/cm^2$



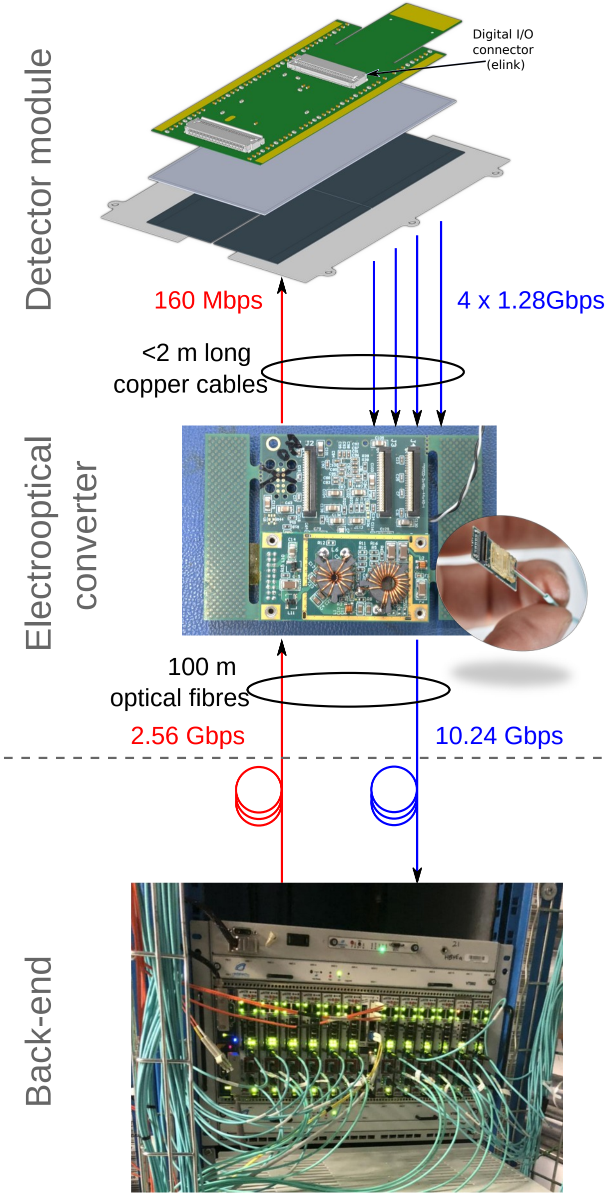
Example: CMS Phase-2 Pixel Detector

Electro-optical conversion in detector volume

- Laser generators and DC-DC converters in detector
- Differential copper connections per module
  - ➔ Material budget
  - ➔ Maximum speed per link: 1.28 Gbps
  - ➔ 1.2 kW of electrical power

➔ Restriction on granularity and trigger rate

➔ Limits physics reach!



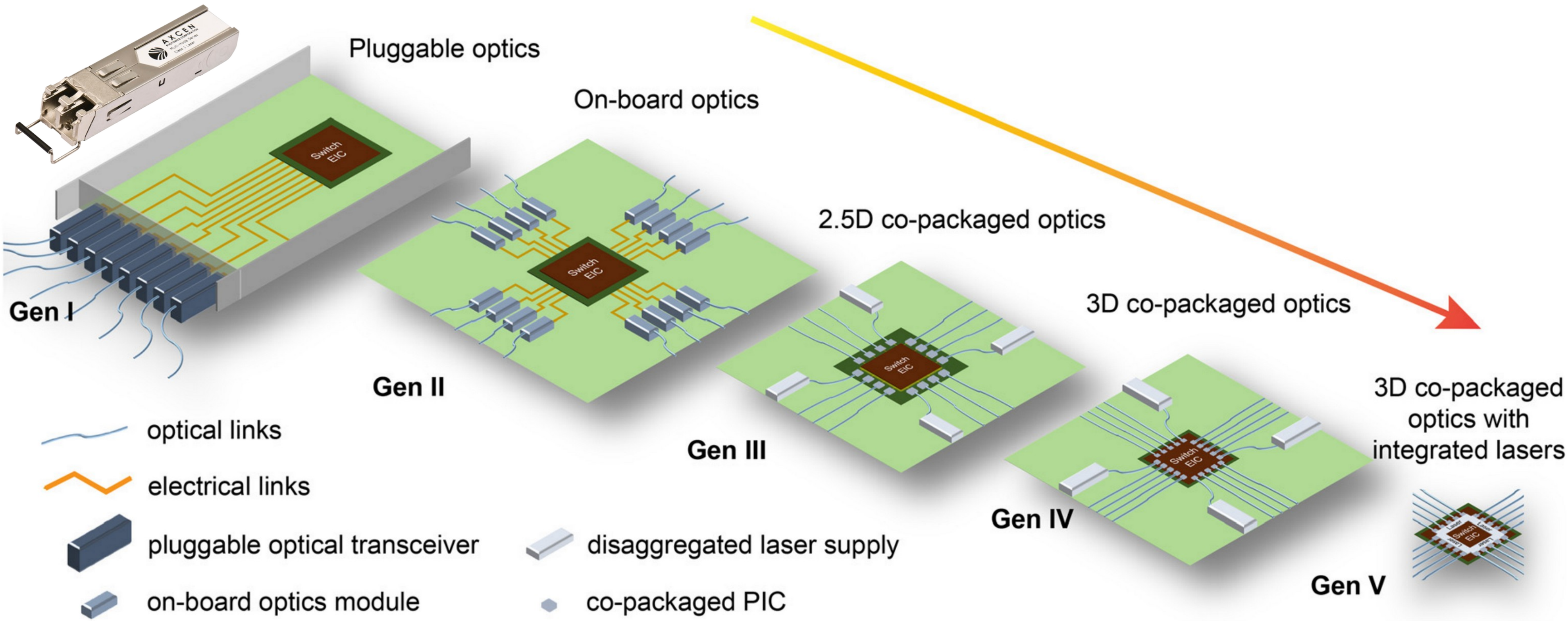
Transmission systems

- Miniaturisation is key for technological advancement
  - Speed, power consumption
- Limits due to losses in electrical connections

Length	Loss	Application
< 10 mm/0.4 in	1.5dB@14GHz 3dB@28GHz	Bump-to-bump Inside MCP or 3D Stack
< 50 mm/2.0 in	4dB@14GHz 8dB@28GHz	Ball-to-Ball Across PCB
< 200 mm/7.9 in	10dB@14GHz 20dB@28GHz	Ball-to-Ball
< 500 mm/19.7 in	20dB@14GHz 40dB@28GHz	Ball-to-Ball
< 1000 mm/39.4 in	35dB@14GHz	Ball-to-Ball

Ayar Labs – Technical Brief: Optical I/O Chiplets Eliminate Bottlenecks to Unleash Innovation

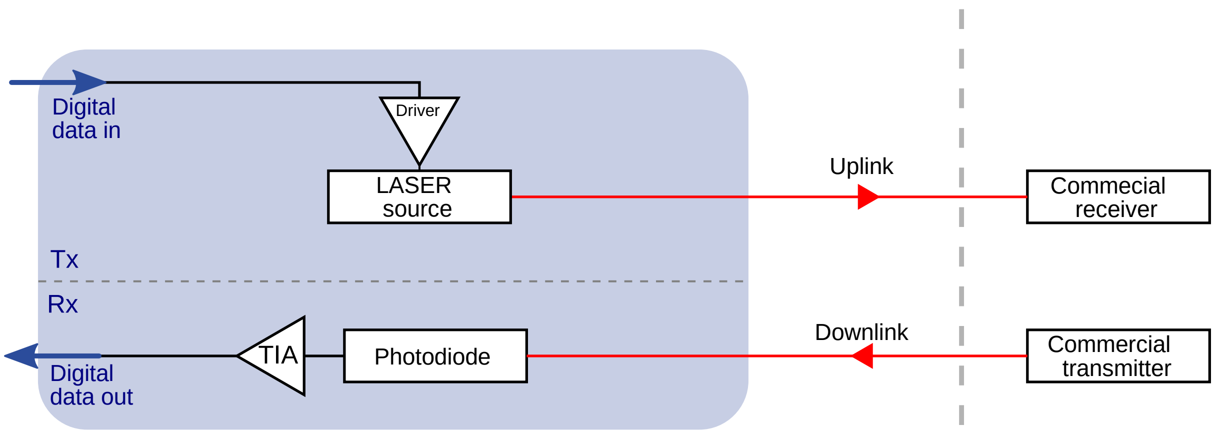
Co-packaging technology

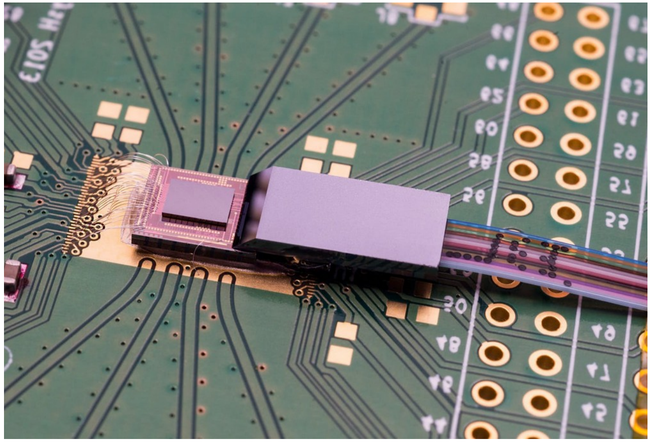


Appl. Phys. Lett. 118, 220501 (2021)

Silicon Photonics

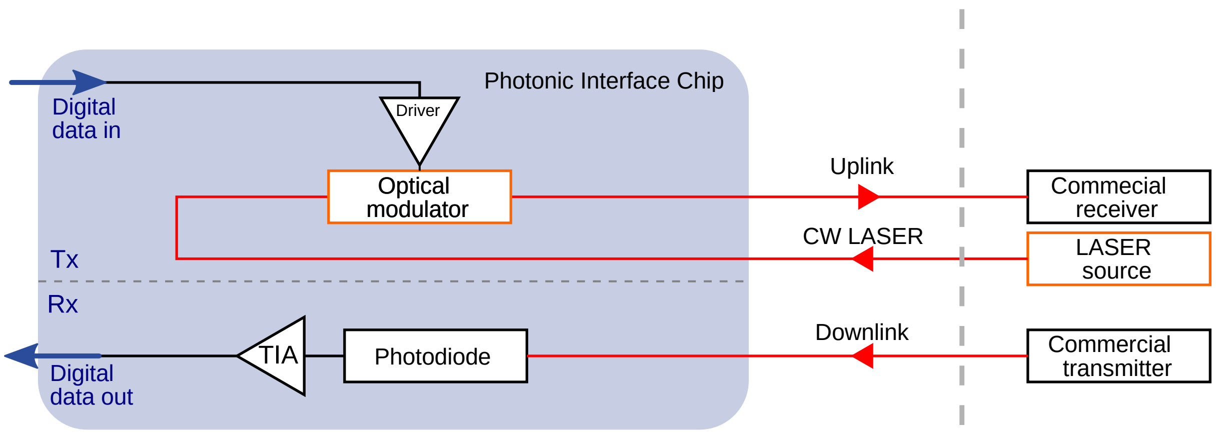
- Developed by telecommunication industry (first idea in 80's)
- Integrate optical data transmission in silicon

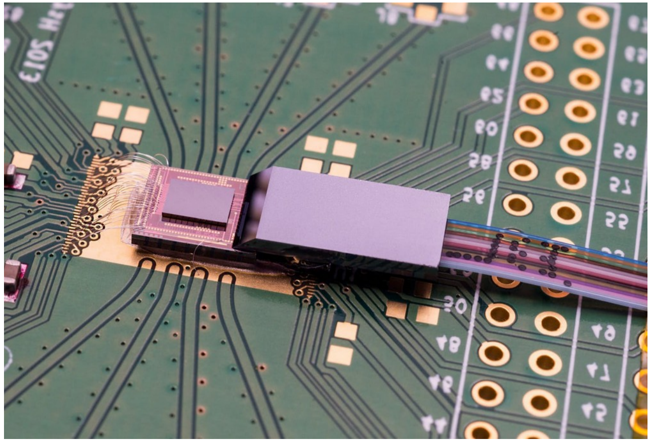




Silicon Photonics

- Developed by telecommunication industry (first idea in 80’s)
- Integrate optical data transmission in silicon
- Light generation → light manipulation on silicon-chips
  - Separation of light generation and modulation
  - Laser source outside electro-optical converter
  - Integration on chip, chiplet or board level

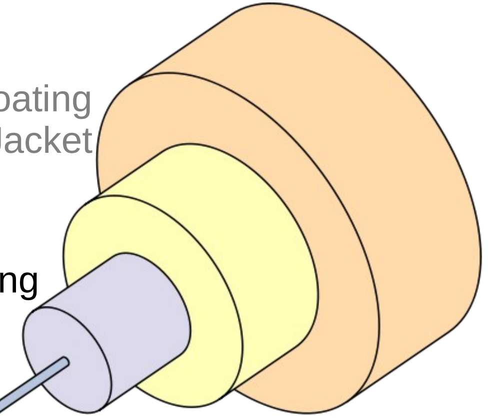




Light guide

Basic principle: total reflection in fibre

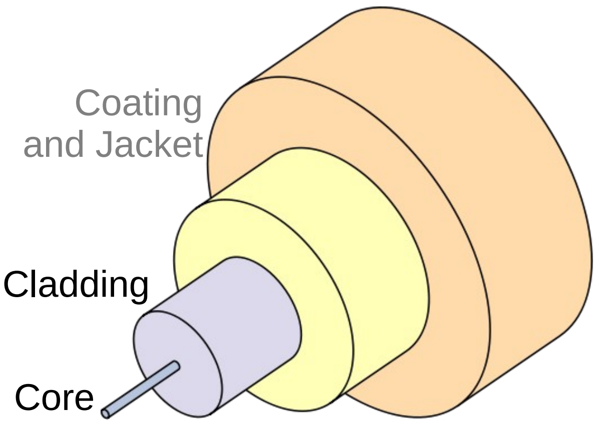
- $n_{Core} > n_{cladding}$

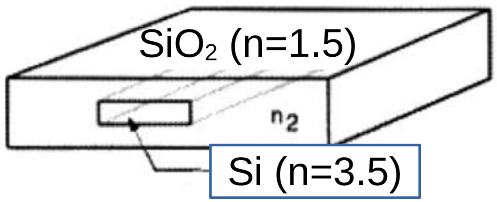


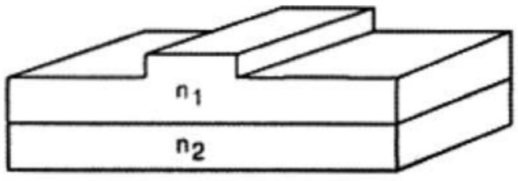
Light guide

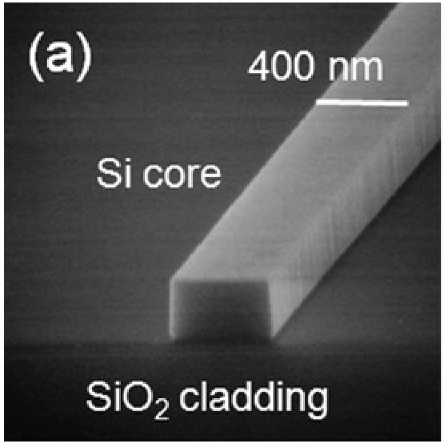
Basic principle: total reflection in fibre

- $n_{Core} > n_{cladding}$
- Silicon-on-Insulator technology
- Silicon core in SiO_2 or Si ridge on SiO_2
- Losses due to scattering (roughness of walls)
  - Doping of ridges, refined processing







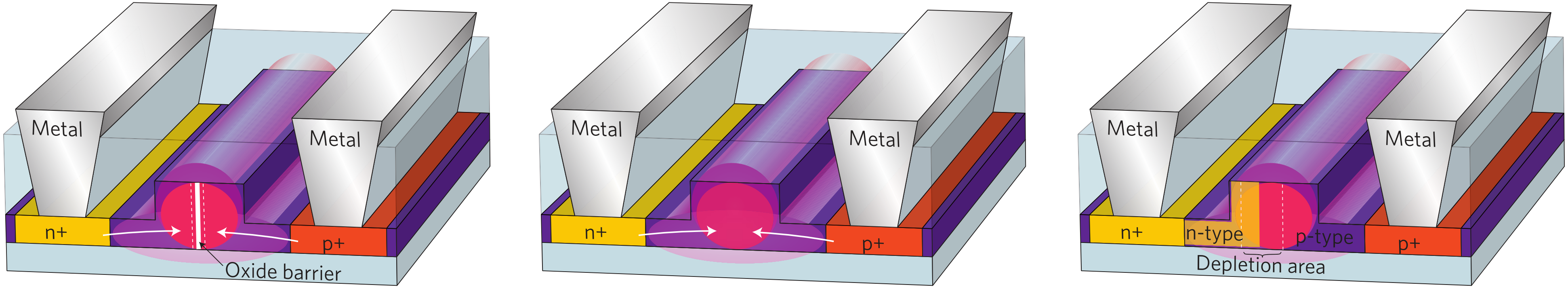


Light manipulation

Absorption and/or phase shifts ➔ control of refractive index

- Thermo-optic effect ➔ large change, but slow (<1MHz)
- Plasma dispersion effect
  - Concentration of free charge carriers changes refractive index

➔ Carrier accumulation, injection or depletion

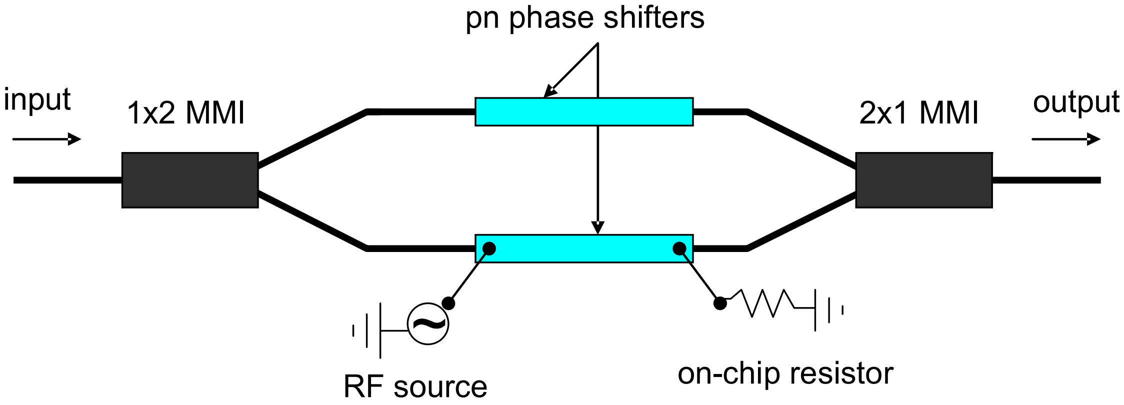


Nature Photonics volume 4, 518–526 (2010)

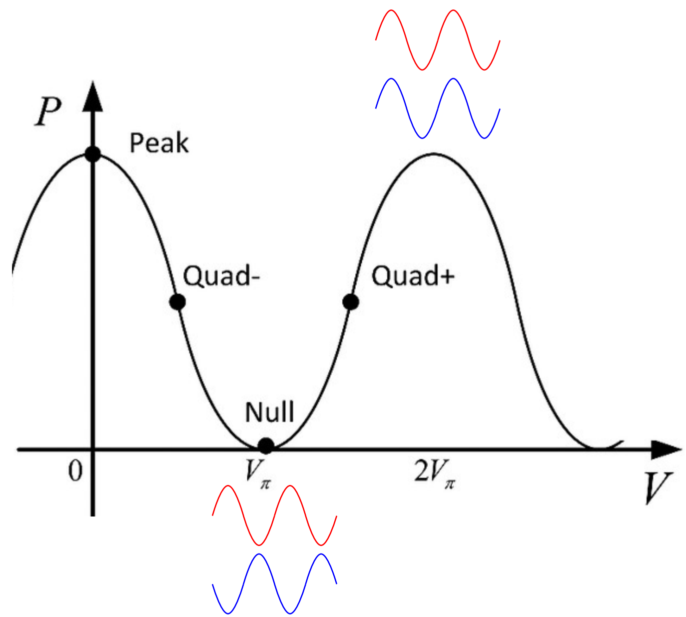
Mach-Zehnder Modulators (MZM)

Two-arm travelling wave interferometer

- Phase shift in one or both arms by application of electric field
- Large bandwidth
- Temperature insensitive
- Rather big footprint (lengths ~1mm)
- High switching voltage (up to 2V)



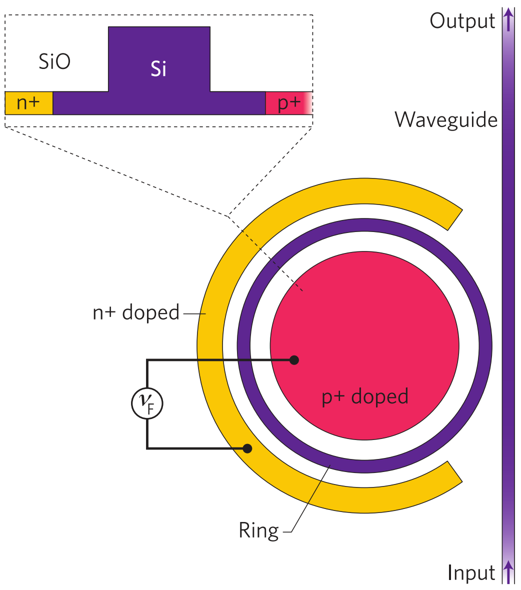
Proc. SPIE 6898, Silicon Photonics III, 68980D

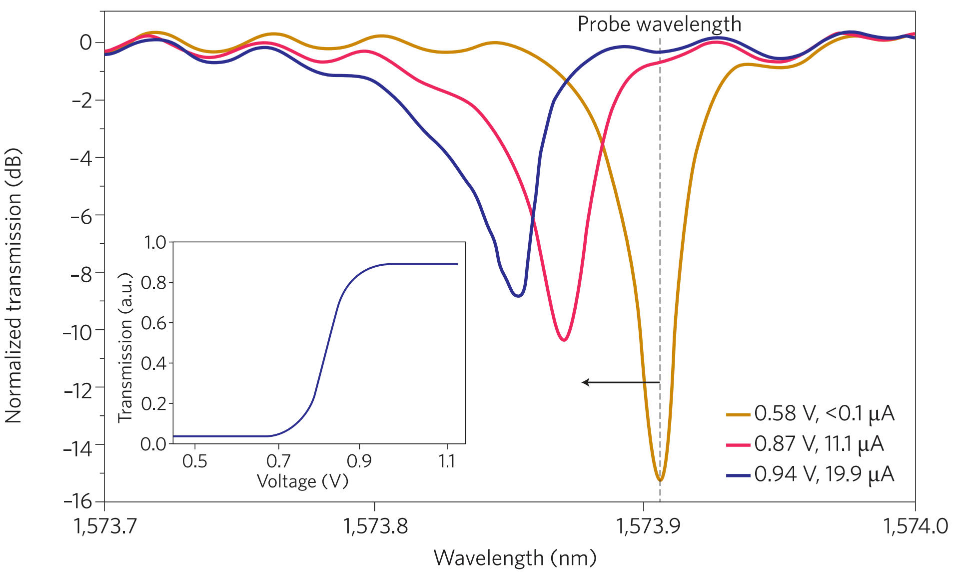


Ring modulators (RM)

Amplitude modulation by resonant absorption

- Tune resonance frequency by applied voltage
- Small footprints (~10µm diameter) and voltages (<1V)
- Temperature sensitive
- Narrow bandwidth



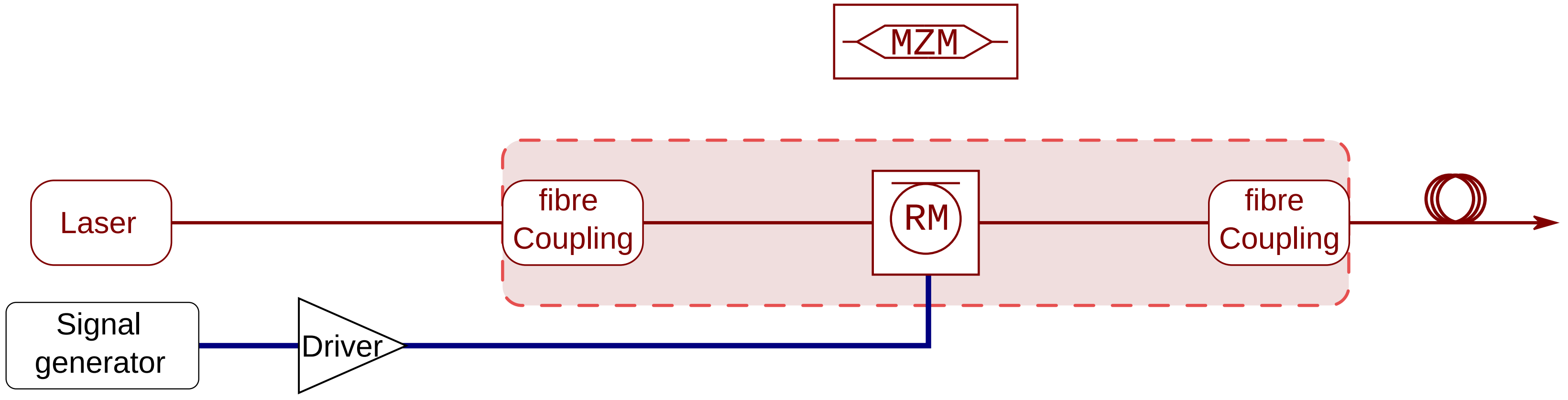


Nature Photonics volume 4, 518–526 (2010)

Data transmission with optical modulators

Up to >25 Gbps through a fibre

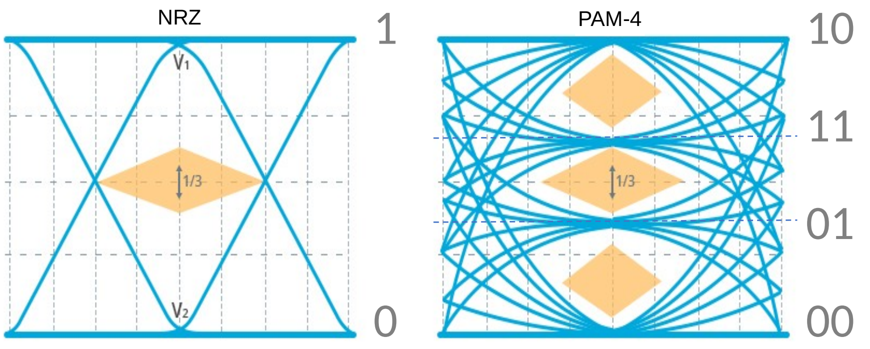
- Driven by external modulators
- Fibre coupling at edge of PIC

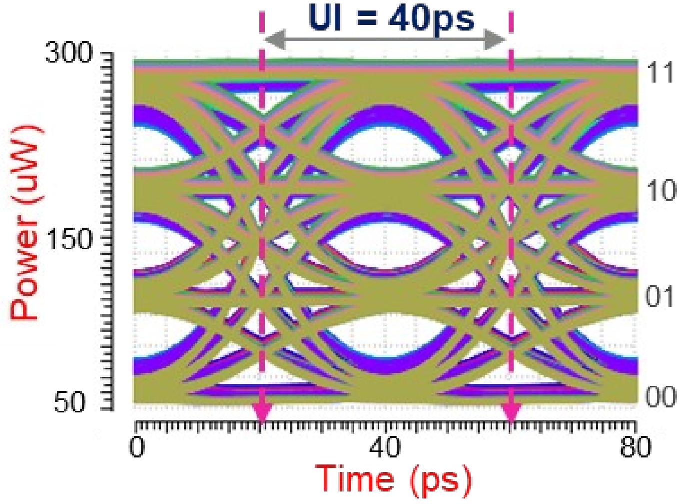


Data rate maximisation techniques

Pulse amplitude modulation (PAM-4)

- Multiple bits per symbol
- Needs wide open region in eye-diagram
- Already in use e.g. by gigabit ethernet
- Needs support from electrical drivers

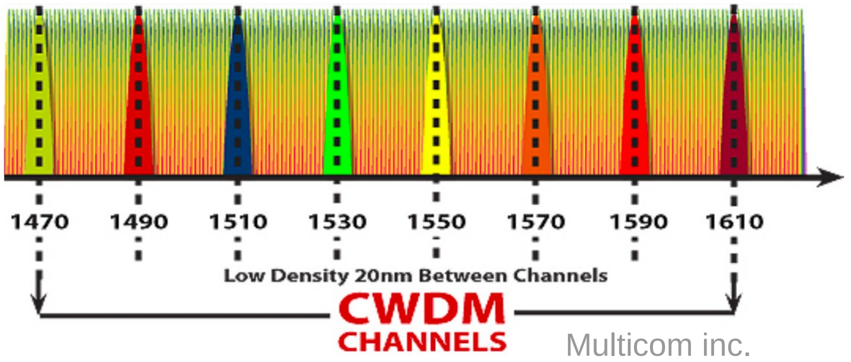




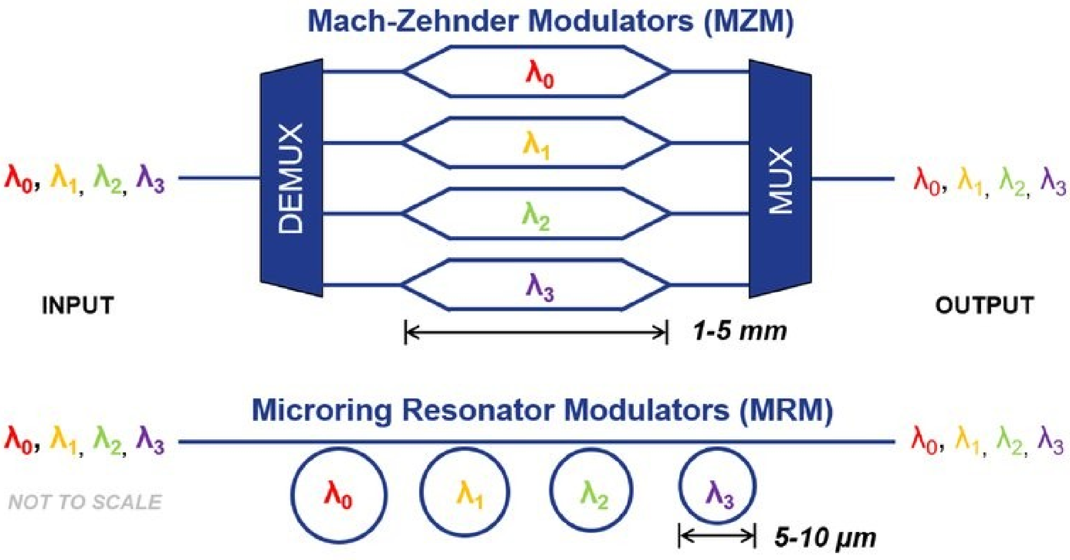
Data rate maximisation techniques

Wavelength division multiplexing (WDM)

- Manipulate multiple wavelengths at the same time
- Broadband laser light necessary
  - Frequency comb
- Compatible to MZM and RM



Multicom inc.



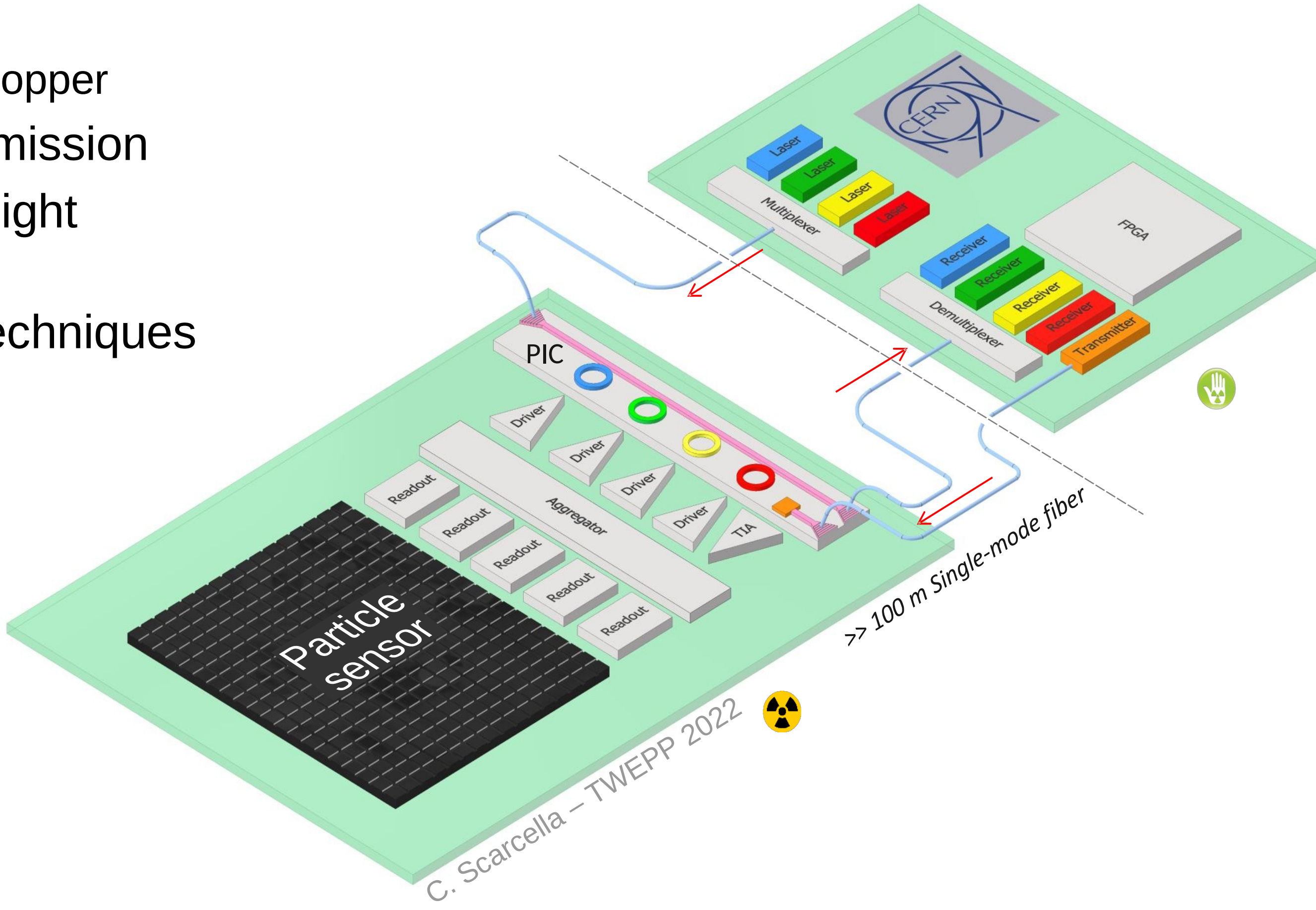
DOI:10.1117/12.2615266

Silicon Photonics for particle detectors

High-speed links on read-out chips

- >25 Gbps per transmitter
  - Currently 1.28 Gbps via copper
- Clean and low-loss transmission
- Several technologies for light modulation
- Data rate maximisation techniques available

➔ O(100) Gbps per fibre



Application in a detector

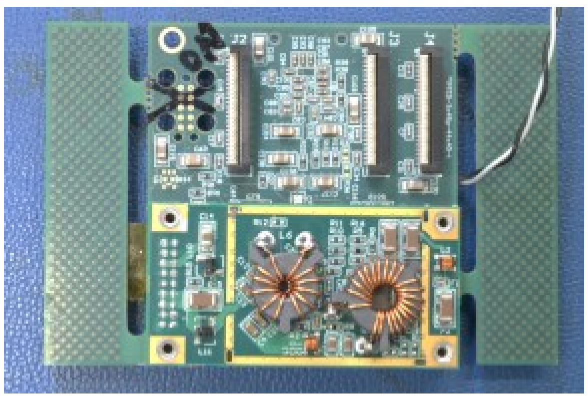
- Dedicated electro-optical converters → Integrated circuit
- Multiple copper connections → Single fibre

→ No converter PCBs

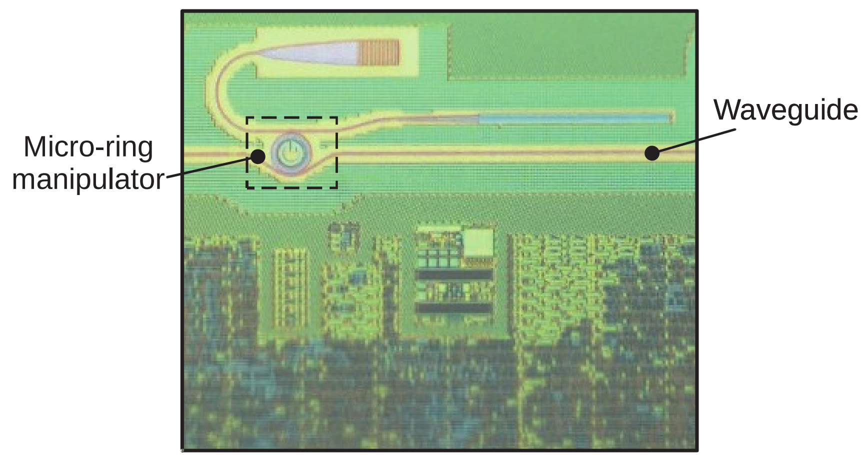
→ No buffering on read-out chips

  → Room for additional circuitry (TDCs,...)

  → Smaller pixel size and higher trigger rates

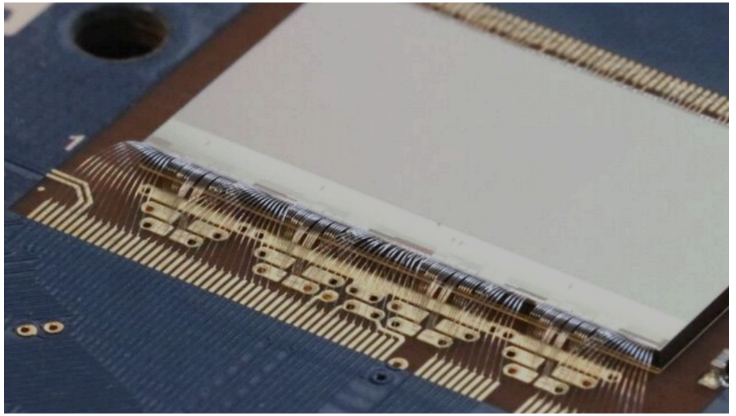


Downsize 1:300



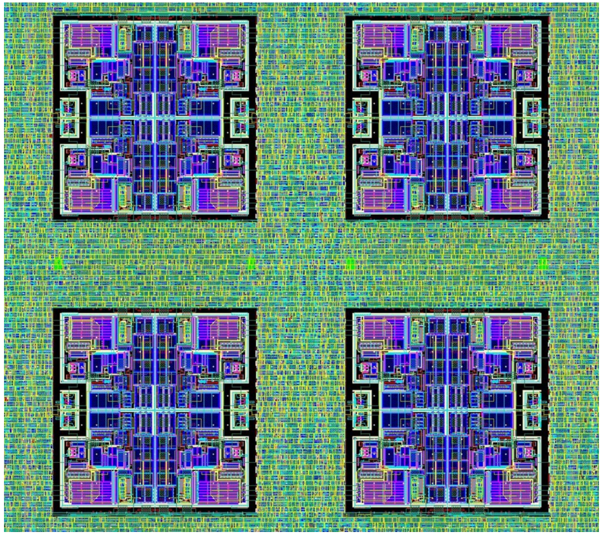
Sun et al., Nature, 2015

RD53 pixel read-out chip in CMS

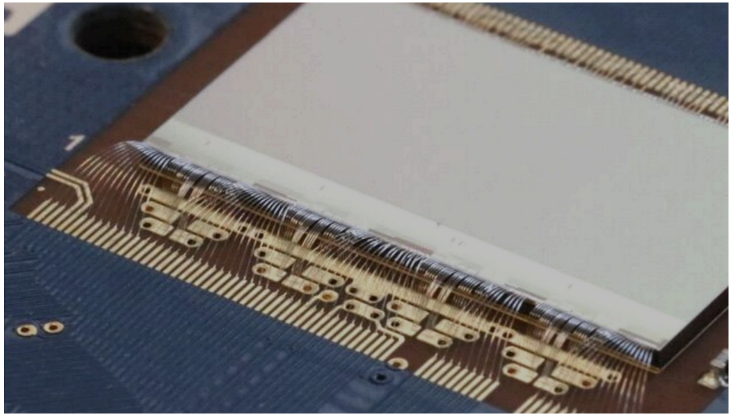


CMS requires 12.5 μs for trigger decision

- ➔ Large buffer for read-out chips
  - ➔ Hit-rate limit due to buffering
  - ➔ Power and real estate
- Large gains of trigger-less readout



RD53 pixel read-out chip in CMS



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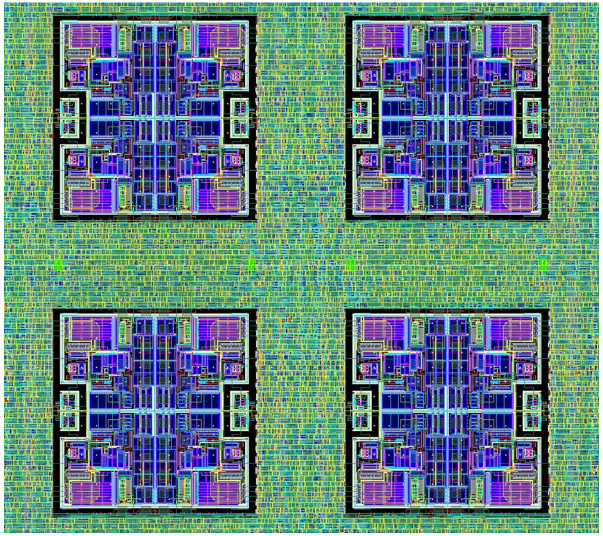
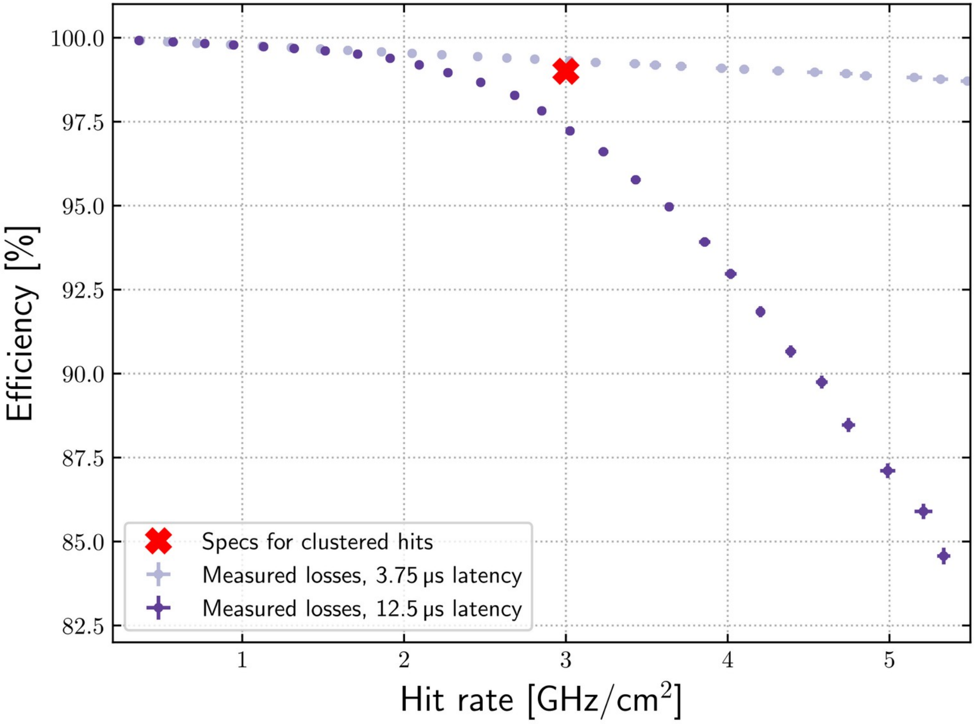
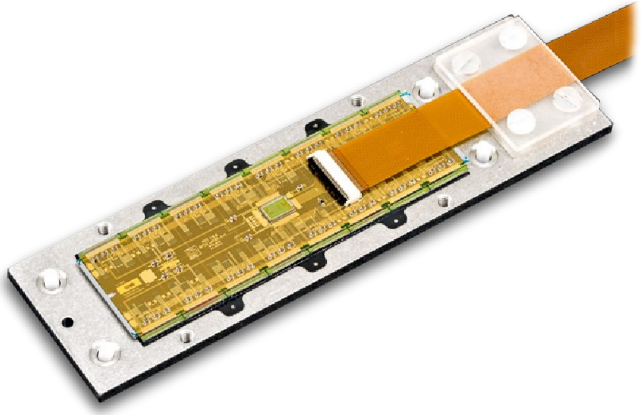


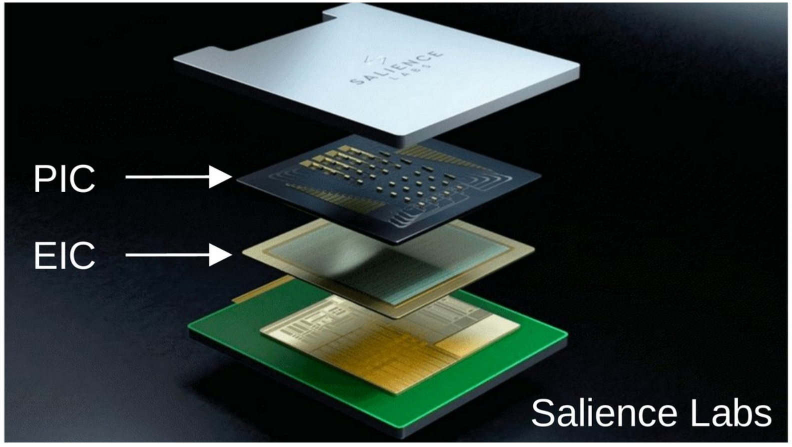


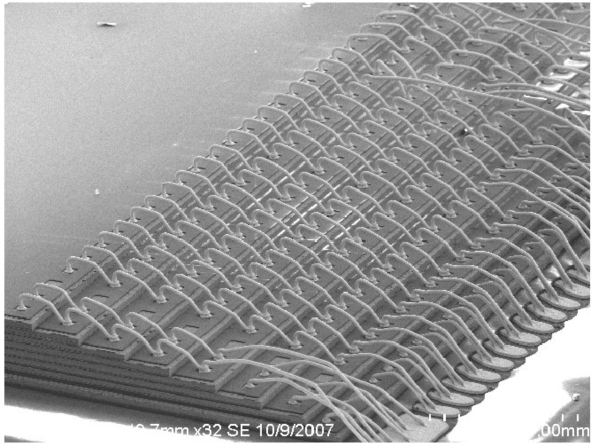
D. Ruini 2019 JINST 14 C10024

Integration

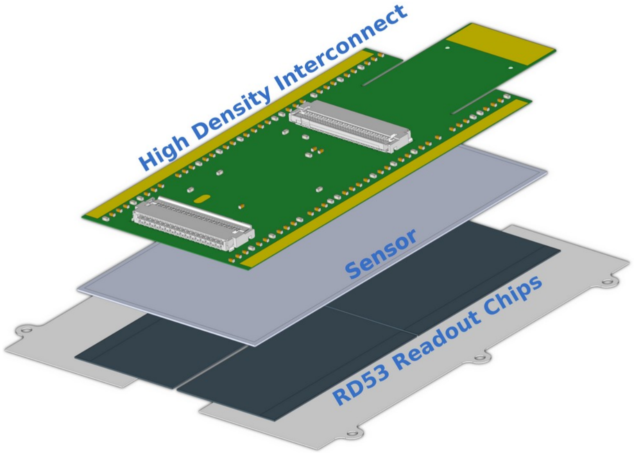
- Silicon-photonics mostly not CMOS compatible
  - ➔ Dedicated PICs and module level integration
- “Add-on” for modules ➔ incremental change
  - Opportunity for next detector upgrades
  - Suitable for MAPS







Opportunity for monolithic sensors



MAPS: Fusion of sensor and read-out chip

- Smaller pixels
- Tailored electronics → less power consumption
- Reduced material budget
- Baseline in many future collider experiments

Silicon photonics data transmission

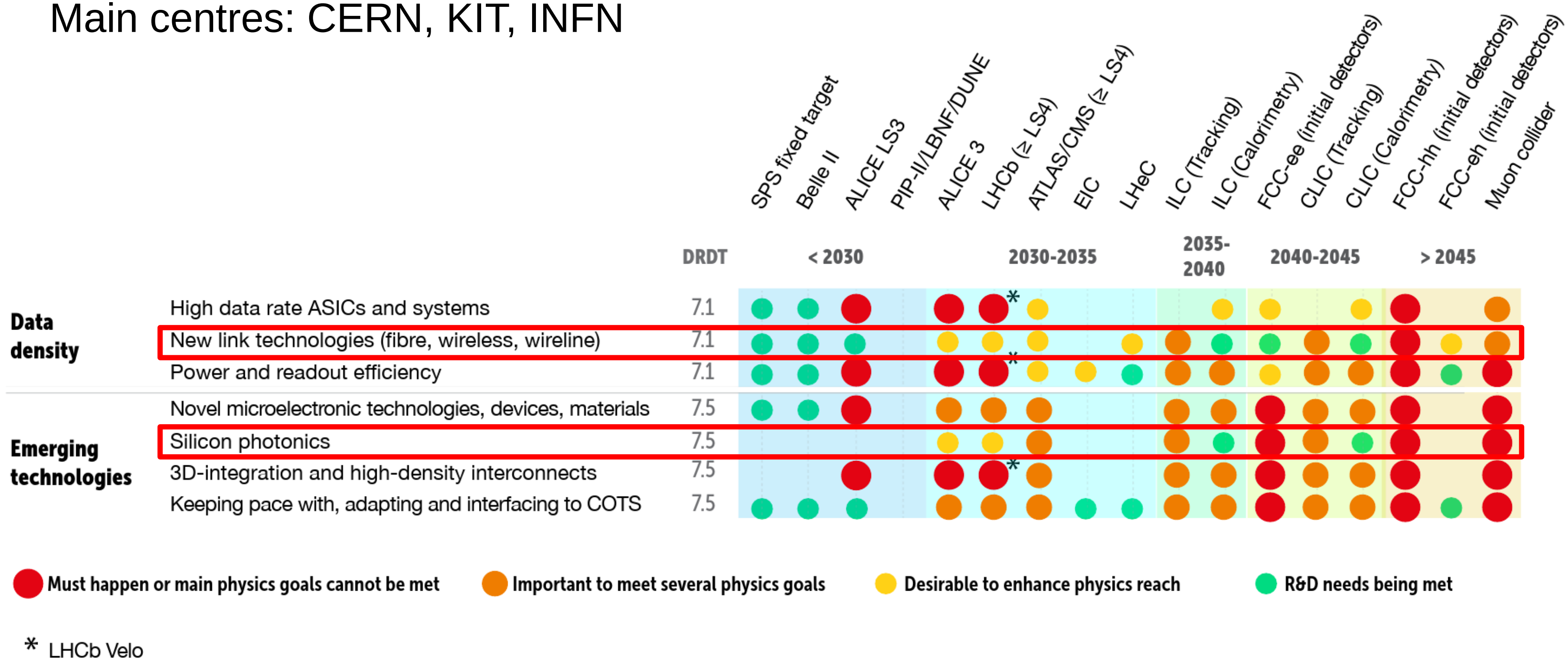
- Hybrid module via flip-chipping / 3D integration
- Slight increase in material, but saving in power
- Complex data handling can be off-loaded

➔ Unlocks full low-material potential of MAPS

Current status in HEP

Active development in HEP community

- Part of ECFA roadmap and Helmholtz strategy
- Main centres: CERN, KIT, INFN



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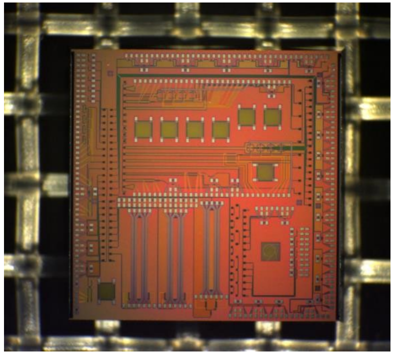
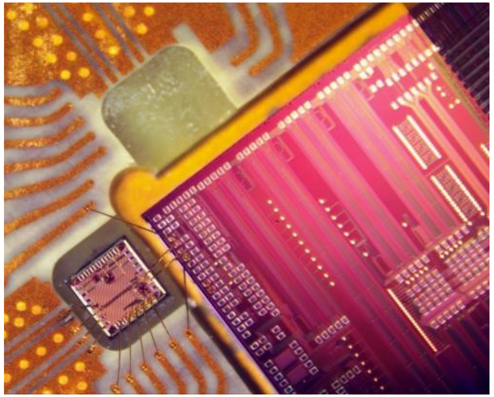
  - Multiple prototypes produced
  - Characterisation of Mach-Zehnder and ring modulators
  - Radiation hardness

PIC by CERN



FALAPHEL PICv1



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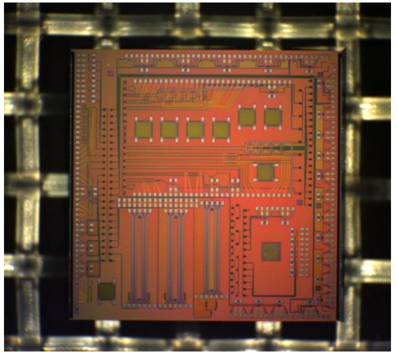
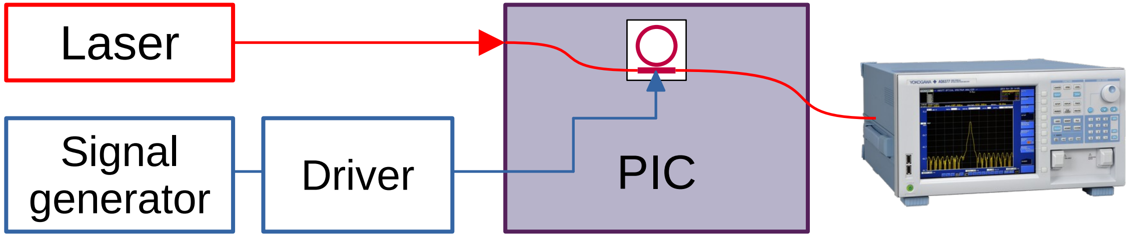
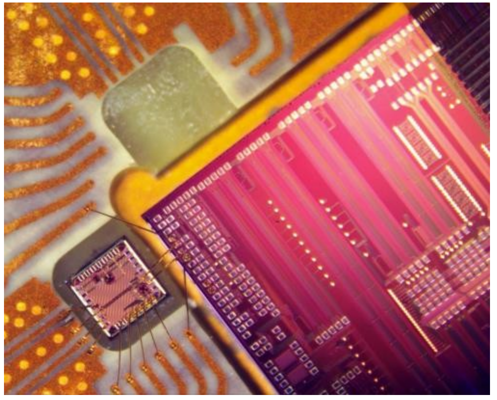




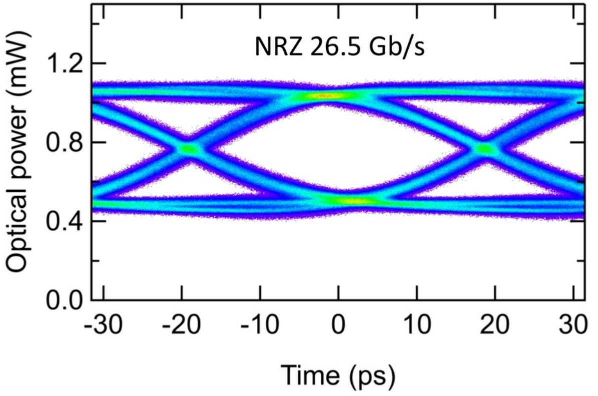
FALAPHEL PICv1



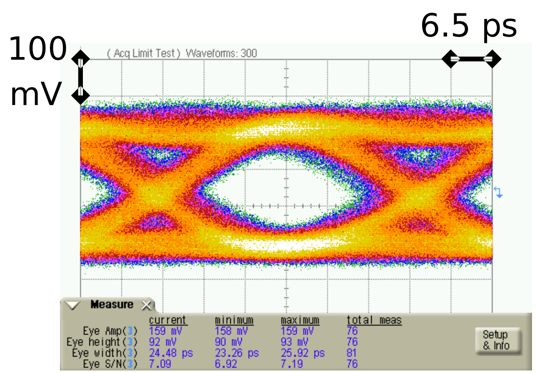
Modulator results – some highlights

CERN and FALAPHEL designs tested up to 40 (26.5) Gbps

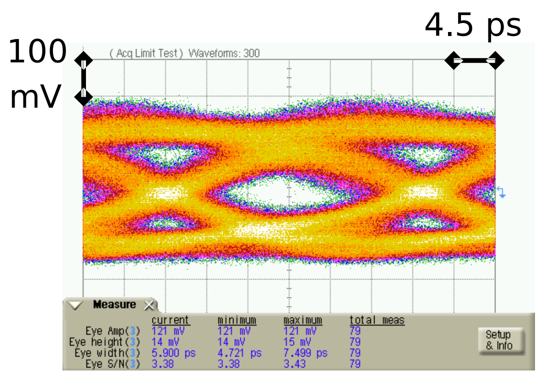
- External drivers for signal generation
  - Commercial drivers and INFN rad-hard driver tested
- Open eye diagrams in both designs



25 Gb/s



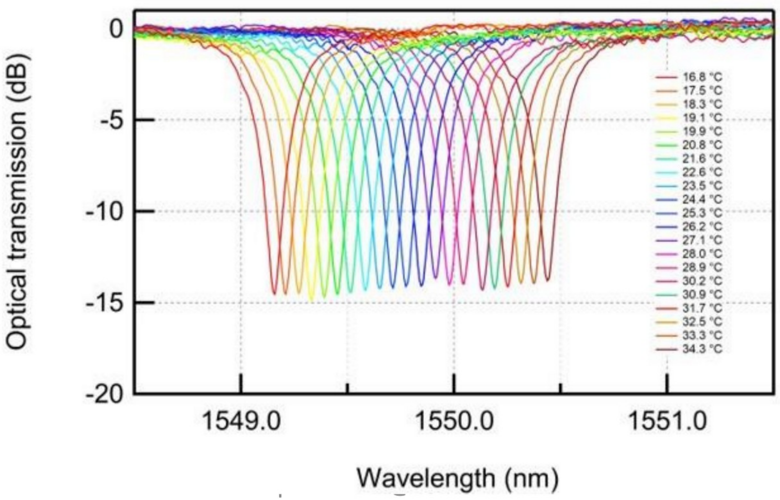
40 Gb/s

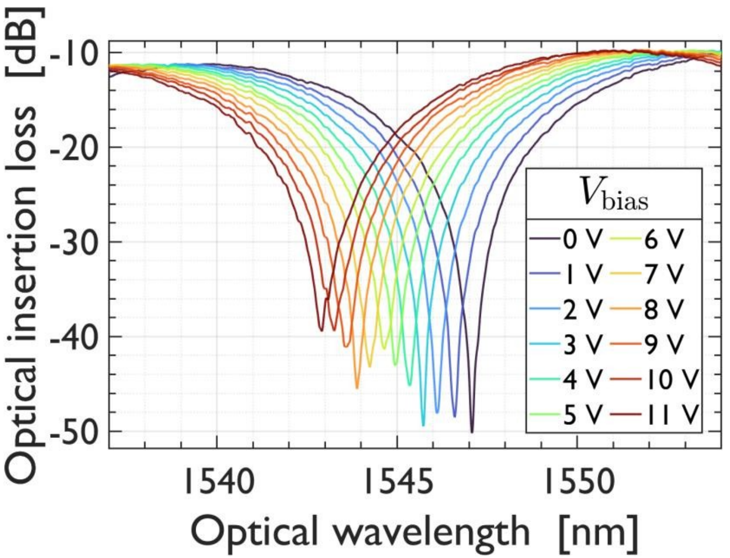


Modulator results – some highlights

CERN and FALAPHEL designs tested up to 40 (26.5) Gbps

- External drivers for signal generation
  - Commercial drivers and INFN rad-hard driver tested
- Open eye diagrams in both designs
- Resonance wavelength of modulators tunable

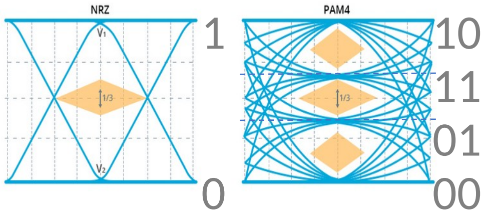


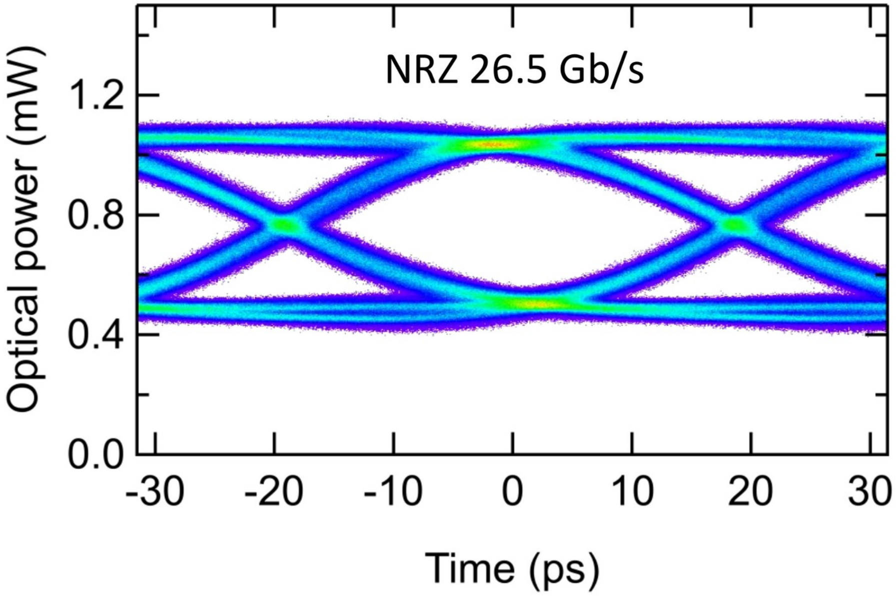


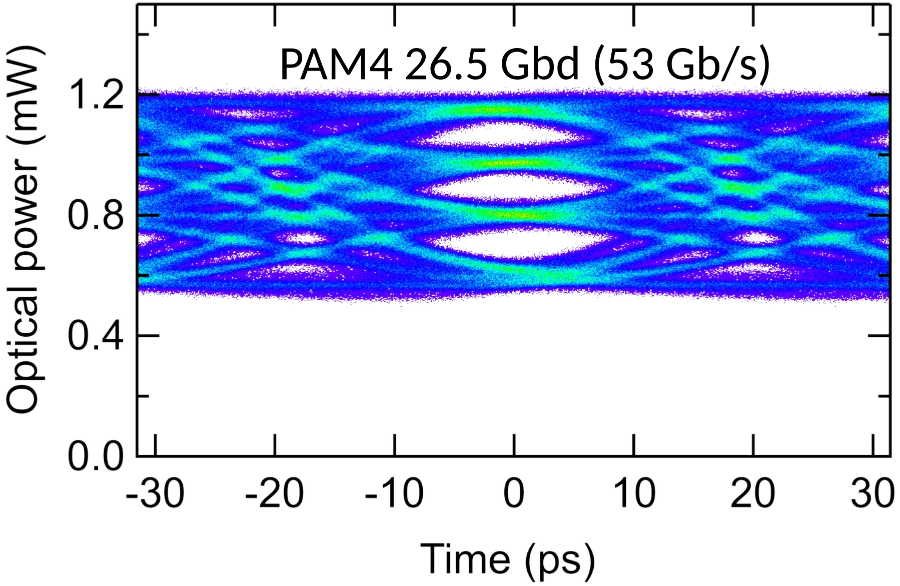
Multiplexing

PAM-4 tested with commercial driver board

- Wide open optical eye diagrams
  - ➔ Clean transmission at 53 Gbps



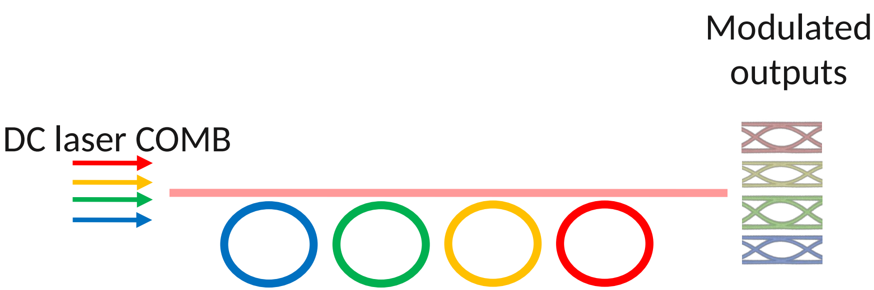


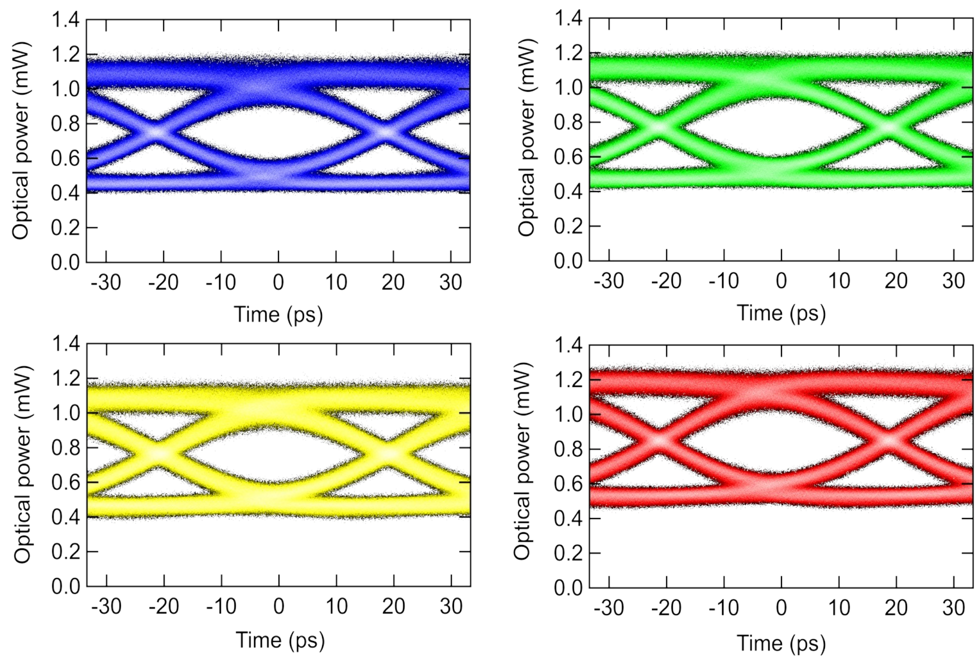


Multiplexing

1:4 wavelength division multiplexing

- 106 Gbps per fibre possible
- Individual drivers
  - ➔ Can be shared by four detectors



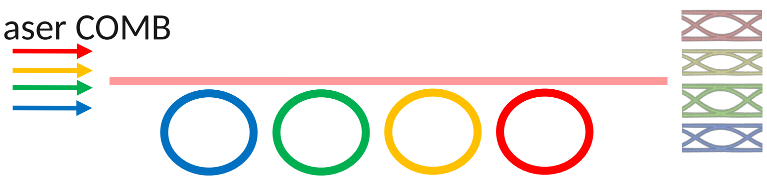


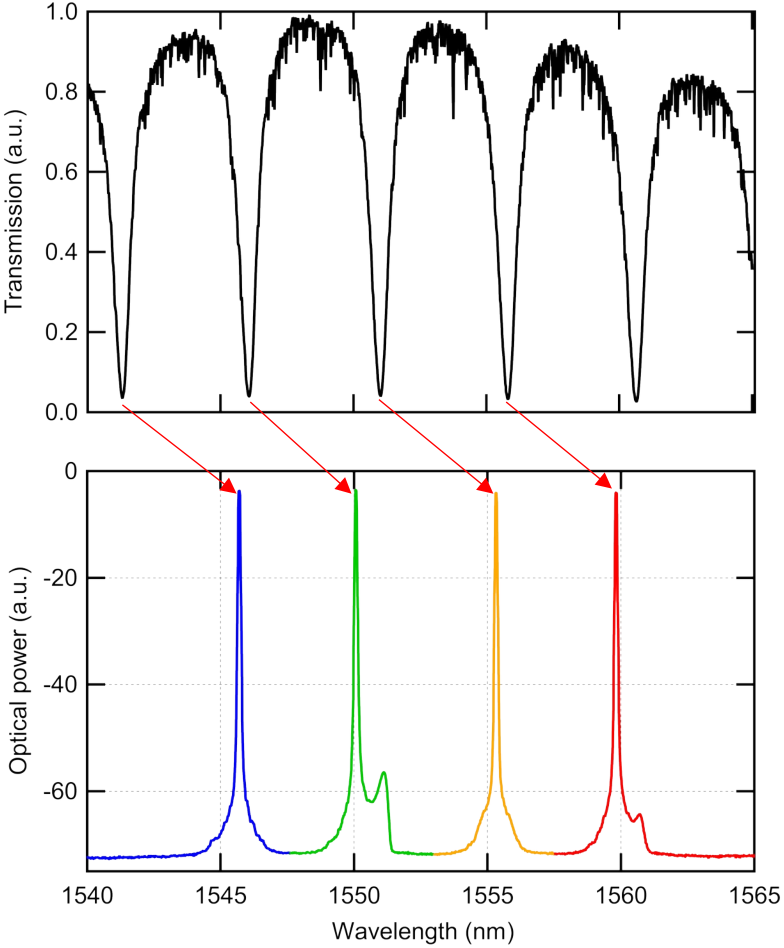
![ETH zürich]

Multiplexing

1:4 wavelength division multiplexing

- 106 Gbps per fibre possible
- Individual drivers
  - ➔ Can be shared by four detectors
- Clear separation, little cross-talk

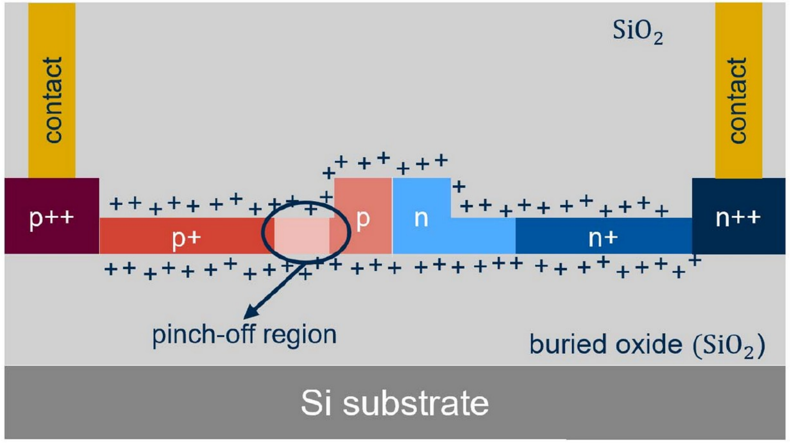




Radiation hardness

MZMs and RMs irradiated up to 10 MGy

- Pinch-off effect in p-doped region



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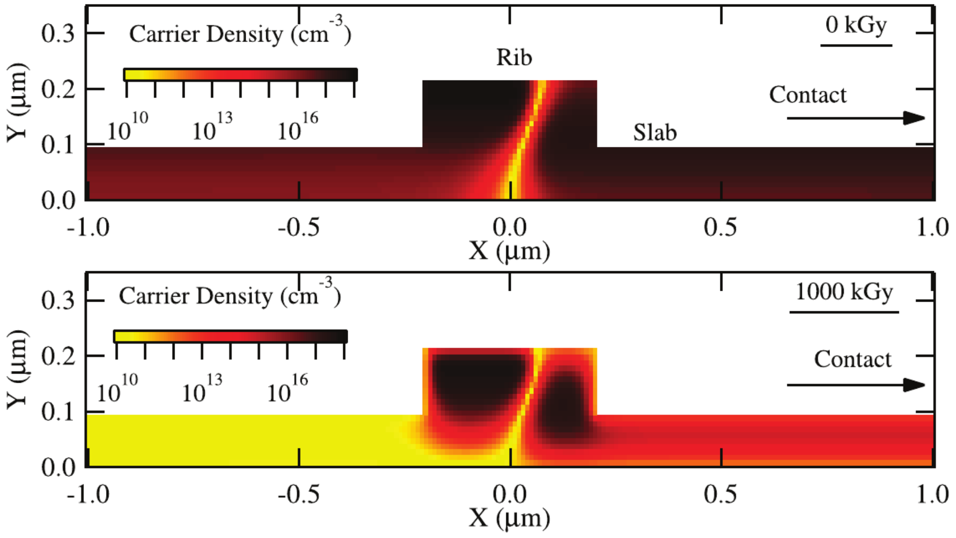

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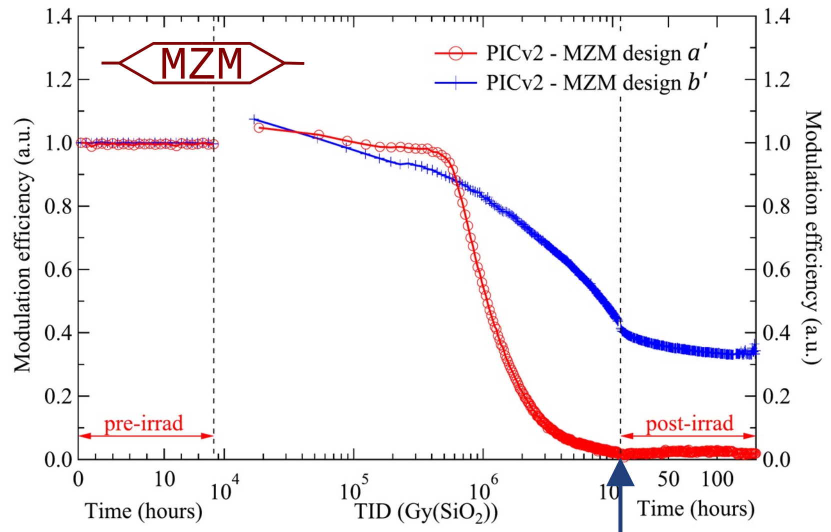
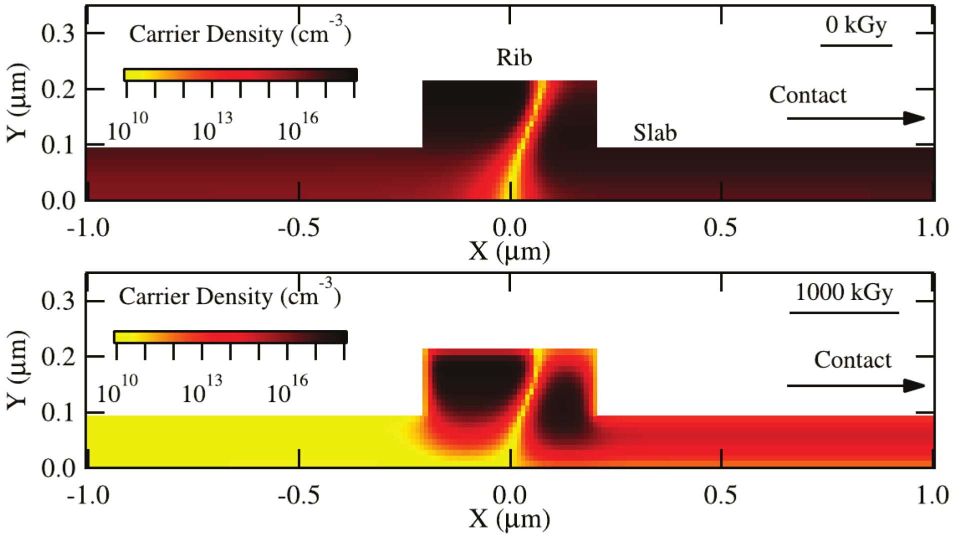
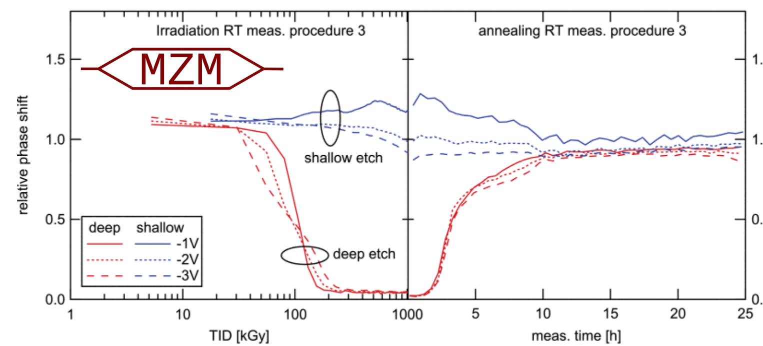


HL-LHC CMS pixel detector TID





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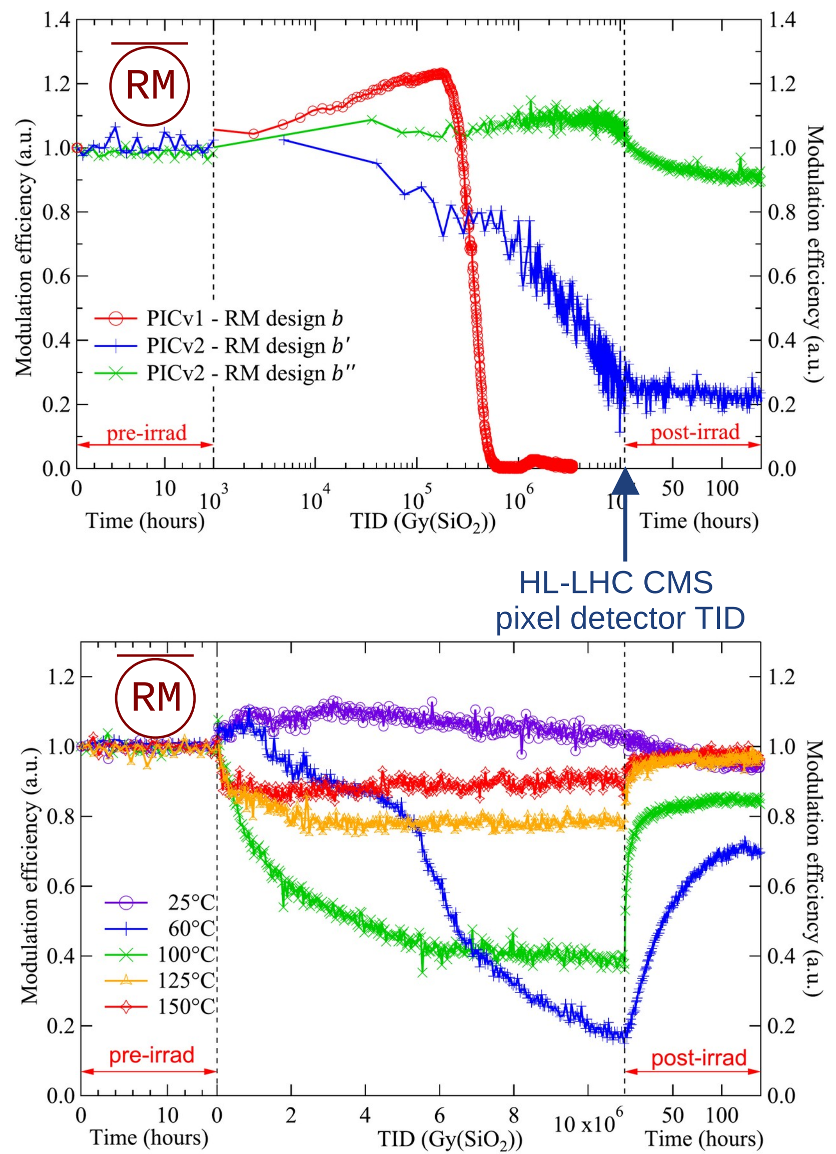
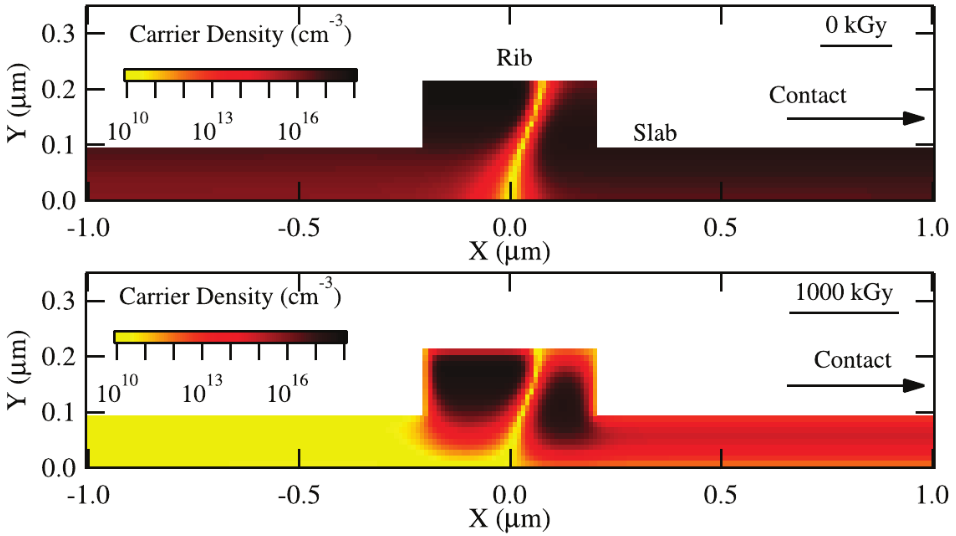
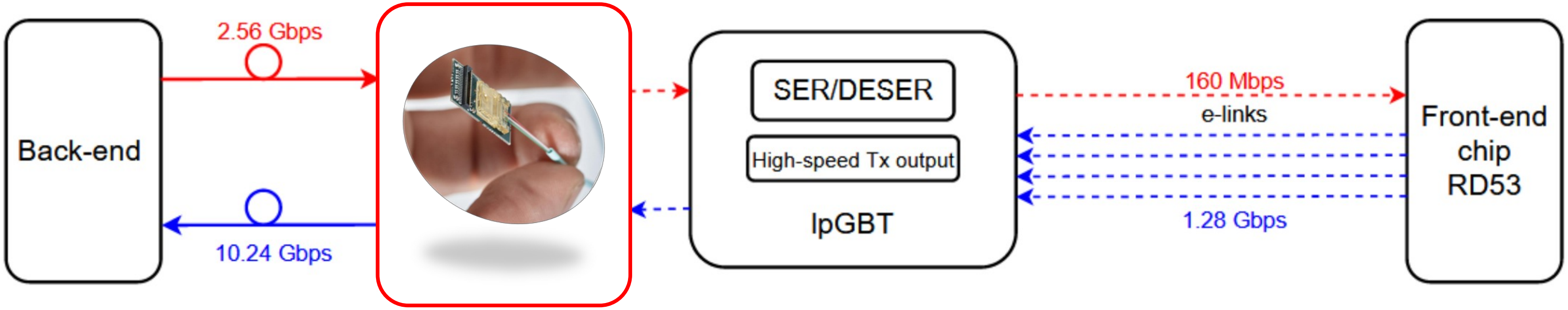




Data transmission with the RD53 read-out chip

RD53A and lpGBT used as direct drivers for optical modulators

- 1.28 and 10.24 Gbps uplink
- Full-duplex link established
- Successful configuration and readout of chip



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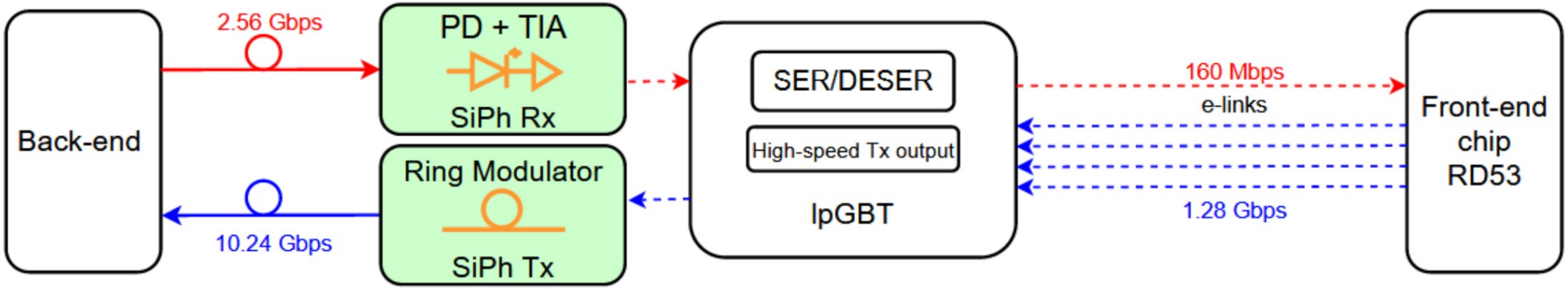

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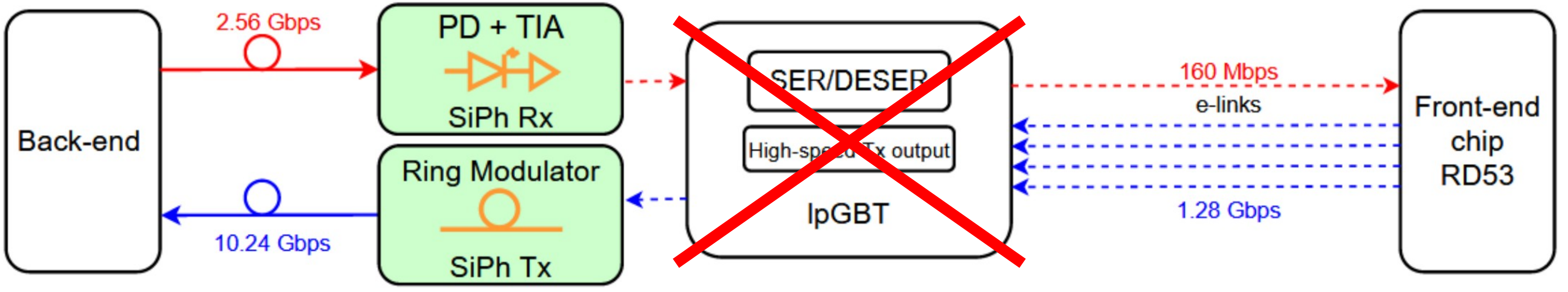
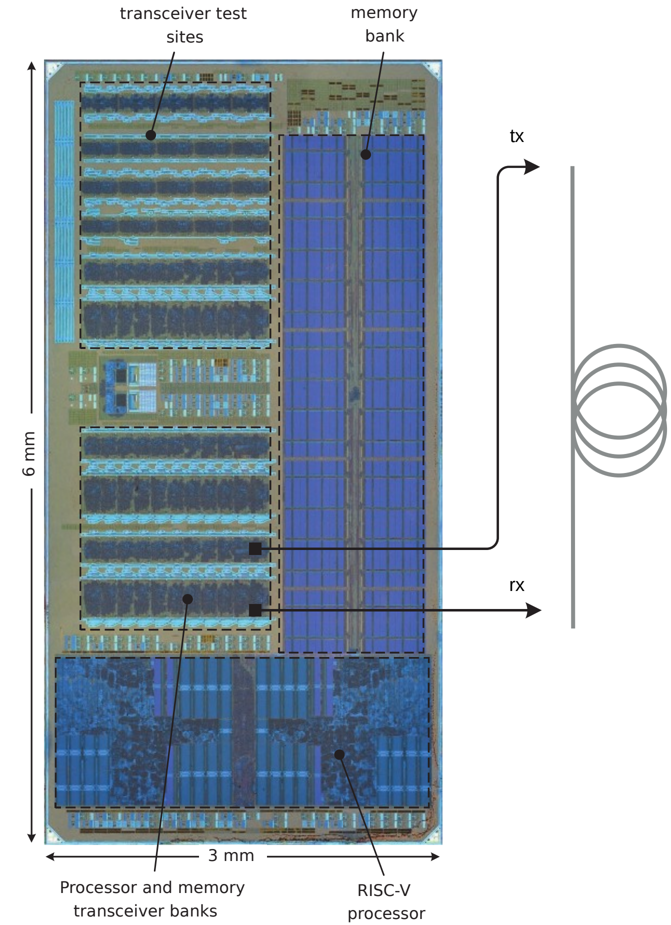


T. Prousalidi – TWEPP 2021 talk

CMOS and silicon photonics

Photonic Microprocessor Chip (SoC)

- Developed as “zero-change” process in 90nm SOI
- RISC microprocessor + memory
- Optical links between CPU and RAM
- 70 Mio Transistors & 850 photonic Devices
- Data transmission: 500Gb/s at 20 fJ/b



Sun et al., Nature, 2015

ETH zürich

GF 45SPCLO: 45nm Silicon Photonics process

State of the art silicon photonics process

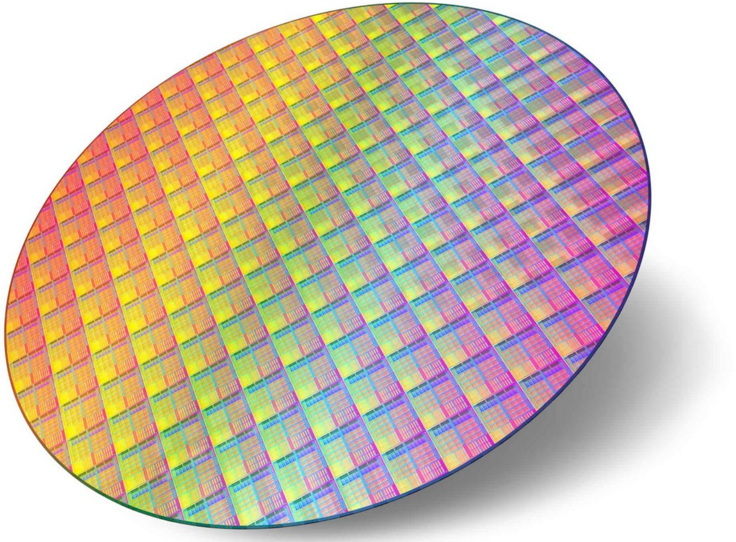
- Monolithic integration
  - CMOS circuitry and photonics on same chip
  - Unique and essential for integration into read-out chips
- Standard library of photonics components
- Supported by multiple design and simulation tools

GlobalFoundries™

Nazca design™
photonic IC design framework

GDS_FACTORY

SYNOPSYS®



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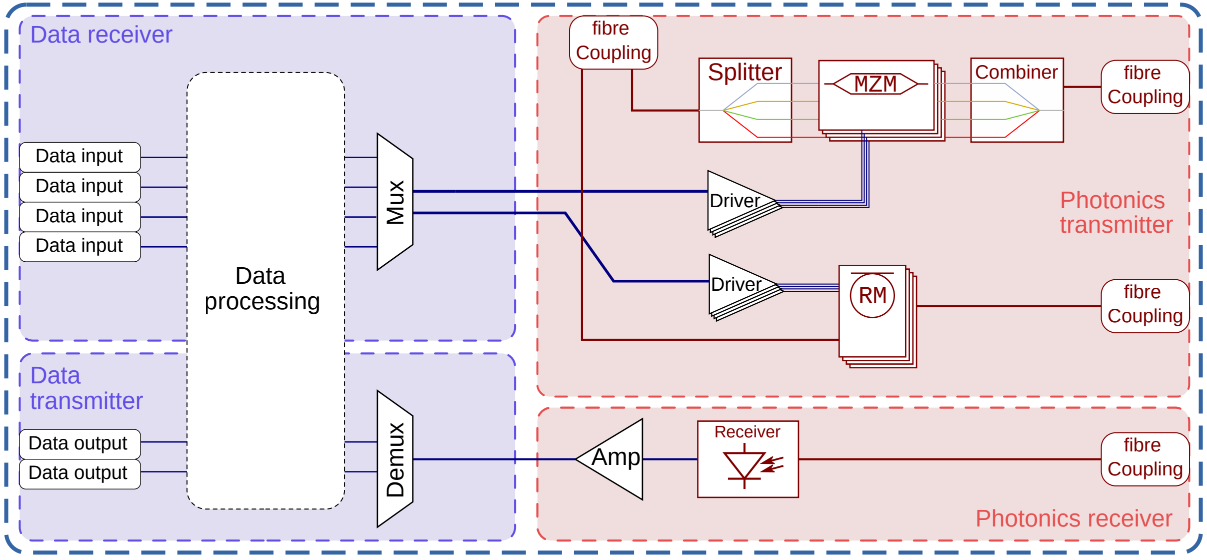
CMOS and silicon photonics for HEP

Fully integrated transceiver

- Versatile and generic due to separate data inputs
- Optimal vessel to introduce silicon photonics to various detectors

➔ Ultimate goal: Pixel read-out chip with integrated silicon photonics



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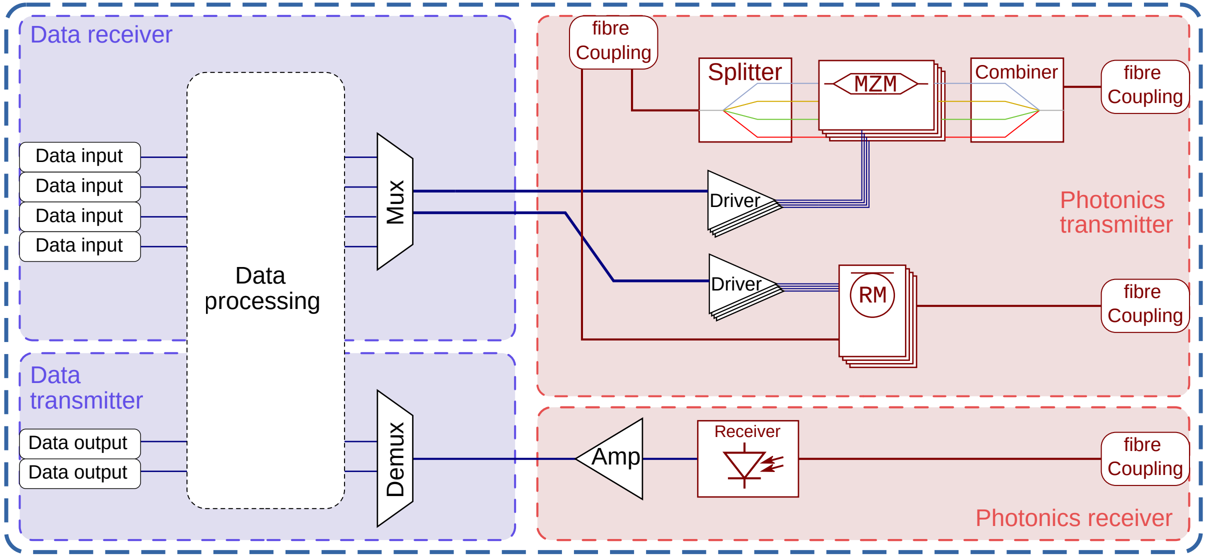
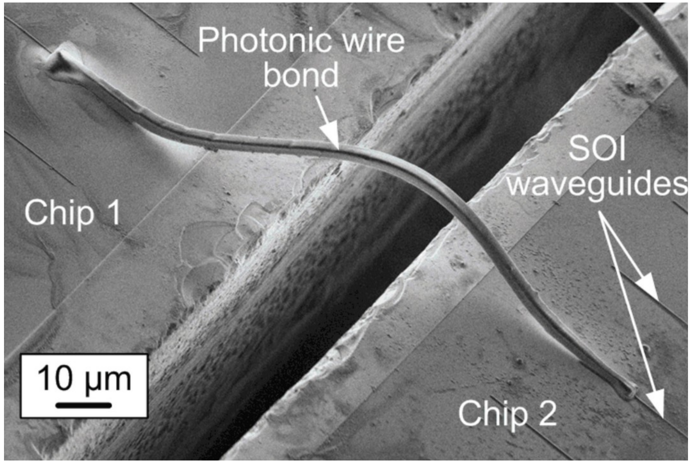




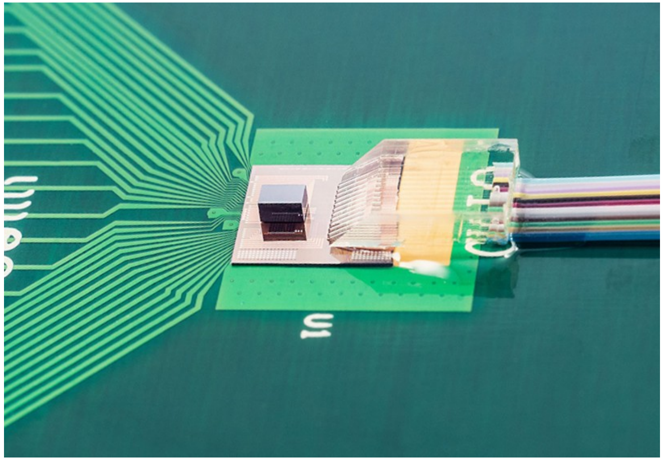
Opt. Express 20, 17667-17677 (2012)

Summary

The future of data transmission from the core of experiments

- High-speed optical links on detector modules
- Significant reduction of power consumption and material budget

➔ New module concepts



- Up to 100 Gbps per fibre demonstrated
- Radiation hard up to 10 MGy

➔ Enables trackers with unprecedented performance

➔ Essential to meet physics goals in HEP and photon science