Towards Silicon Photonics for HEP Detectors

XII Front-End Electronics Workshop

Torino

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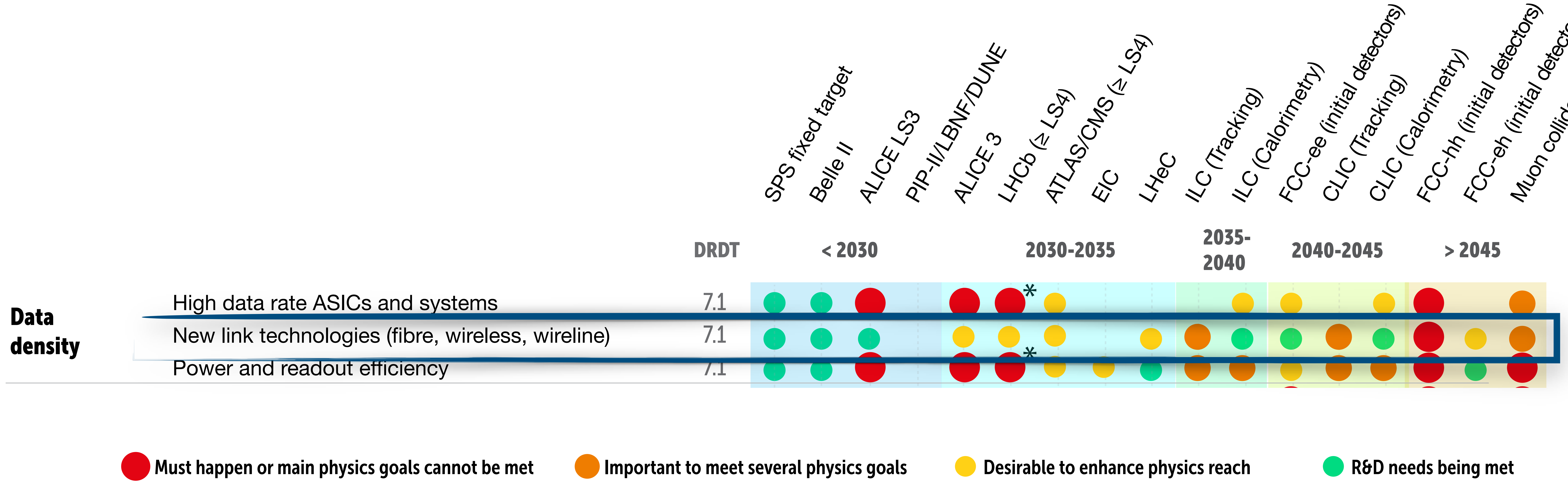
Future experimental challenges



Future experimental challenges

A few examples

Requirement	LHCb (LS $\geq$4)	ATLAS/CMS (LS $\geq$ 4)	HIKE (NA62++)	FCC-hh
Hit rate (GHz/cm^2)	12	6	10	10 (vertex) - 100 (EMCAL)
NIEL (10^{16} n_{eq}/cm^2)	6	1	1	10
TID (MGy)	10	10	10	250
Data rate (100 Gbs/cm^2)	1	1	0.2	1 - 10

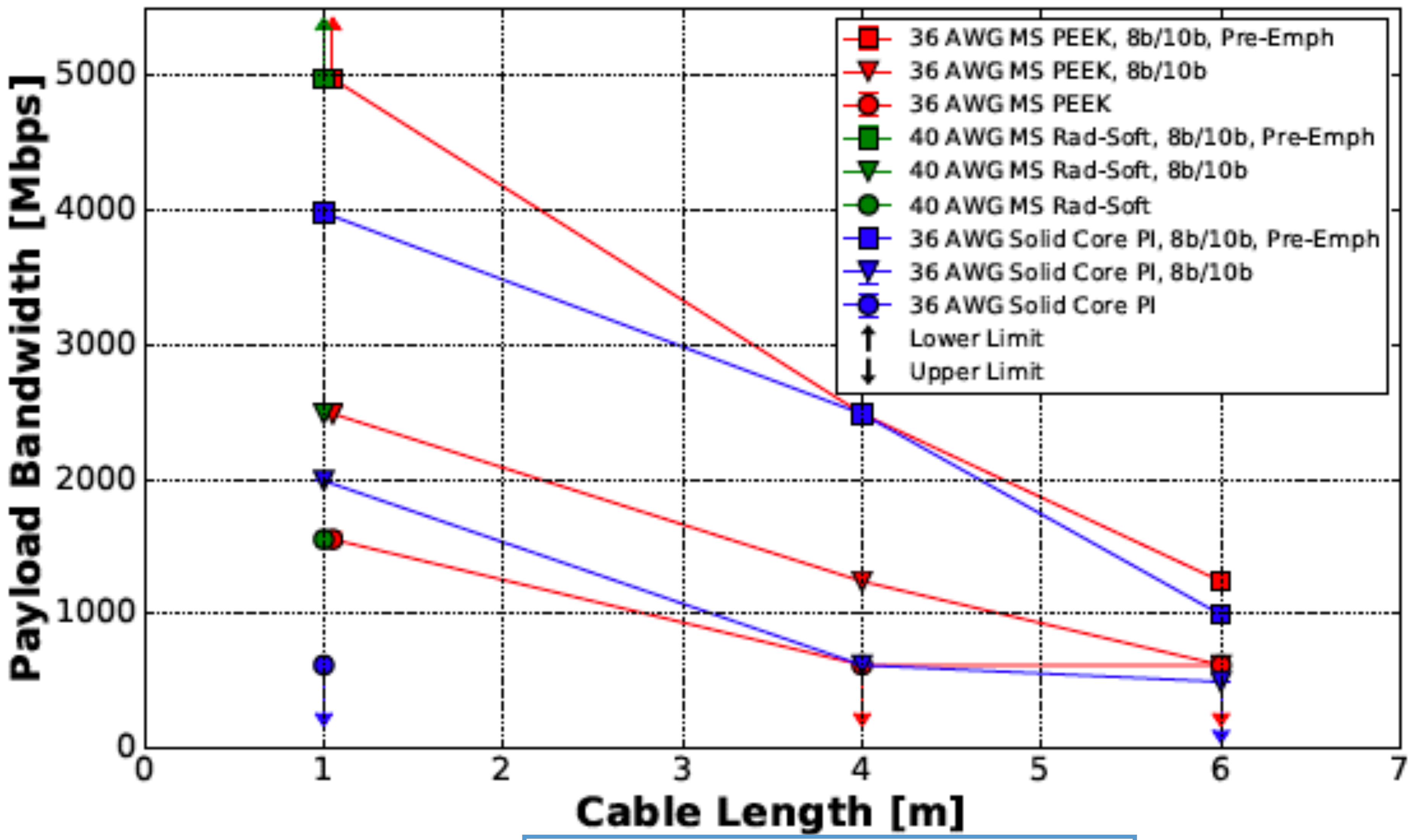
State of the art

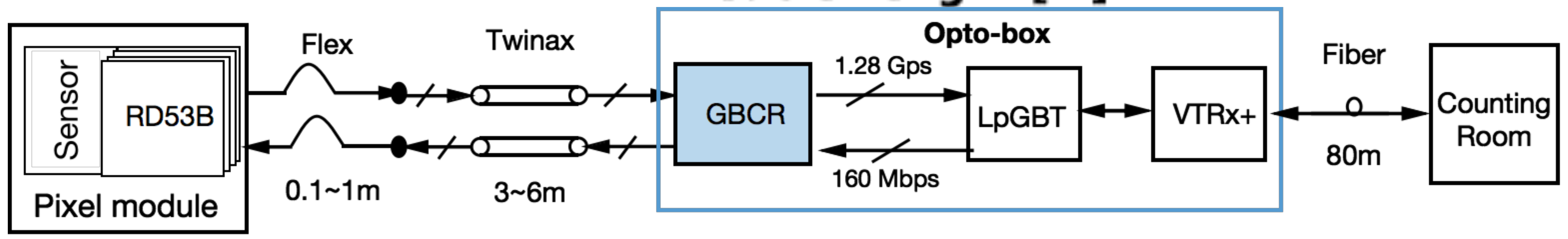
- **Current high-speed links are based on opto-electronics (VCSEL based) technology**
- **Radiation hardness is the major problem**
    - Currently used high-speed circuits (LpGBT, 10.5 Gb/s) are not qualified for TID exceeding 0.5 Grad and few 10^{15} n/cm^{2}.
  - Alternatives are being explored using
    - New optoelectronic devices, with laser sources placed outside the high-radiation zone
    - New physical layers
- **Electrical low-mass cables do not provide high-enough data rate and are limited to relatively small distances.**

Electrical low mass cables

How far and how light can we go?

- **ATLAS/CMS R& Phase-II upgrade**
    - ATLAS (6m) needs an additional ASIC to match input specs for LpGBT





- *Advanced modulations schemes (PAM-4, QAM etc) must be deployed to reach faster speed*
    - The first CMS pixel detector readout used an analog scheme with address levels coded into six levels.

https://doi.org/10.1016/j.nima.2006.05.038.

Silicon Photonics based links for HEP

Telecommunication networks standard

- Allow very high speed performances (100G are the standard for data centres)
- Several technologies allow high-speed modulation of light from an electrical source
- Several modulation schemes (NRZ, PAM4, QAM) and multiplexing schemes (WDM, SDM, PDM) - although more or less difficult to implement - can be used to increase overall bandwidth while keeping “manageable” (up to 25G) the single lane speed
  - Intra-Data centres connections use highly parallel systems where a large system of fibres (or more generally optical cores or optical modes) must be deployed in a constrained space.
    - Applicable for FCC-hh ?
- In the past few years extensive R&D (particularly at CERN) has understood the mechanisms to increase radiation hardness of the devices

Silicon for Optics

Pros and Cons

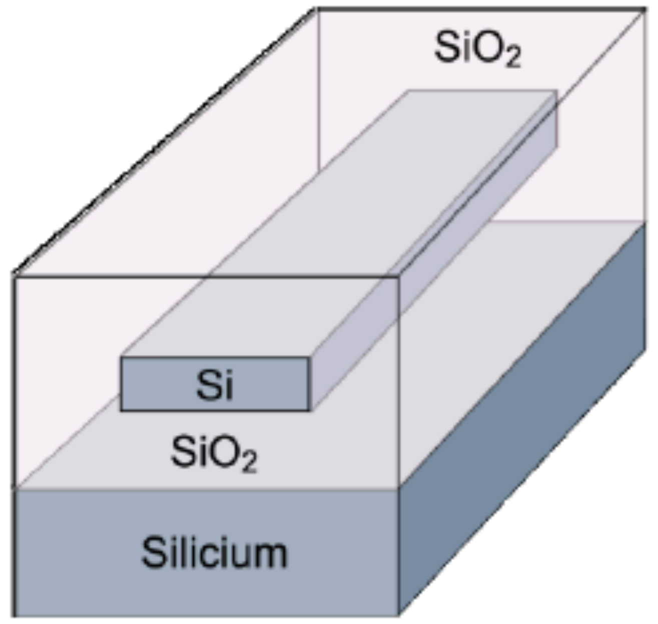
- **Pros**
  - Transparent in the region 1.3 to 1.6 μm (Low loss waveguides)
  - Take advantage of mature CMOS platform (Mature technology and high mass production)
  - Low costs
  - Silicon on Insulator (SOI) wafer
  - High contrast (nSi=3.5 nSiO2=1.5) (strong light confinement and small footprint)

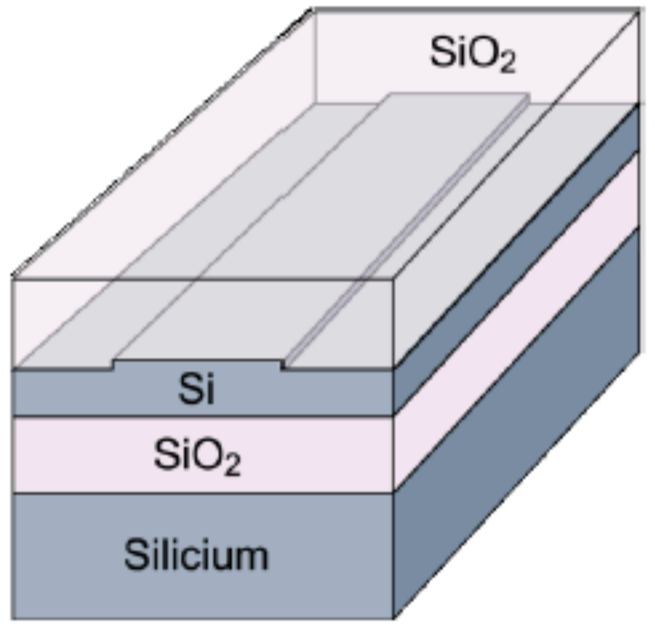
- **Cons**
  - Indirect bandgap material (no or weak electro-optic effects - no Silicon laser)
  - No detection in the 1.3 - 1.6 μm region
  - Large mode mismatch with fibre

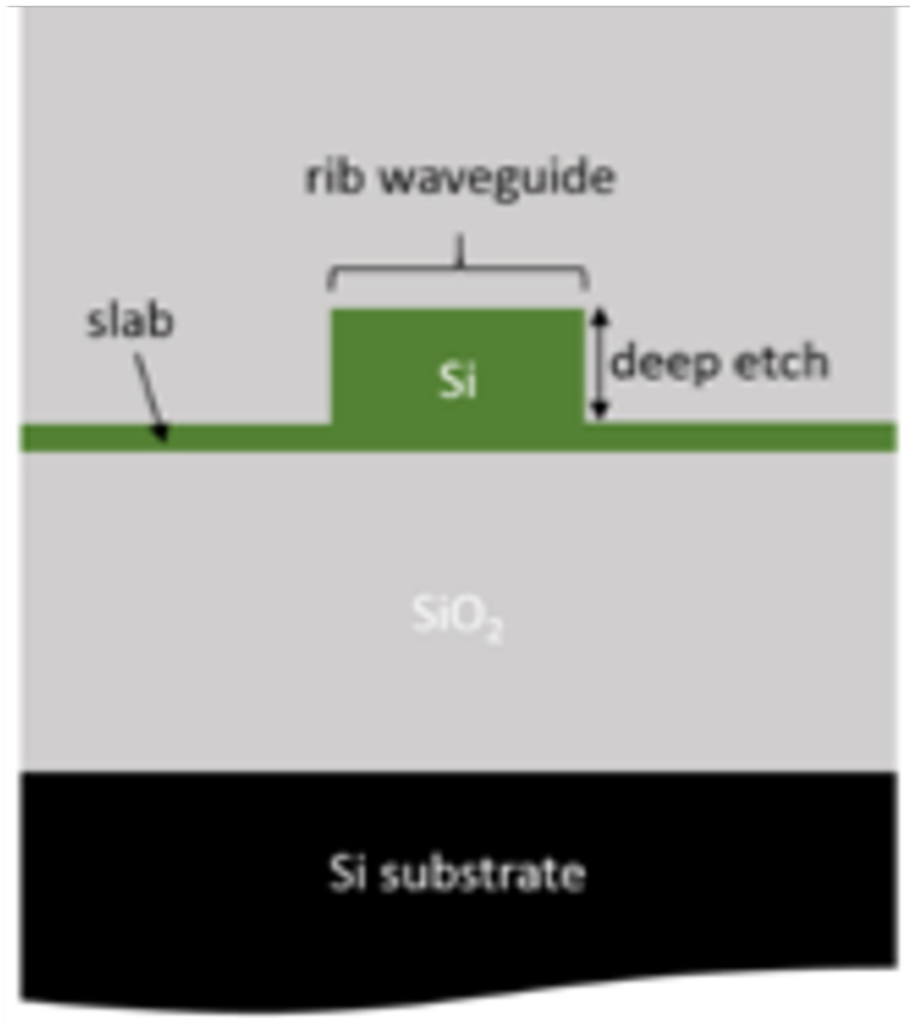
Process devices

Waveguides

- **Silicon optical waveguides**
  - Silicon on insulator substrate
  - Rib or strip waveguide



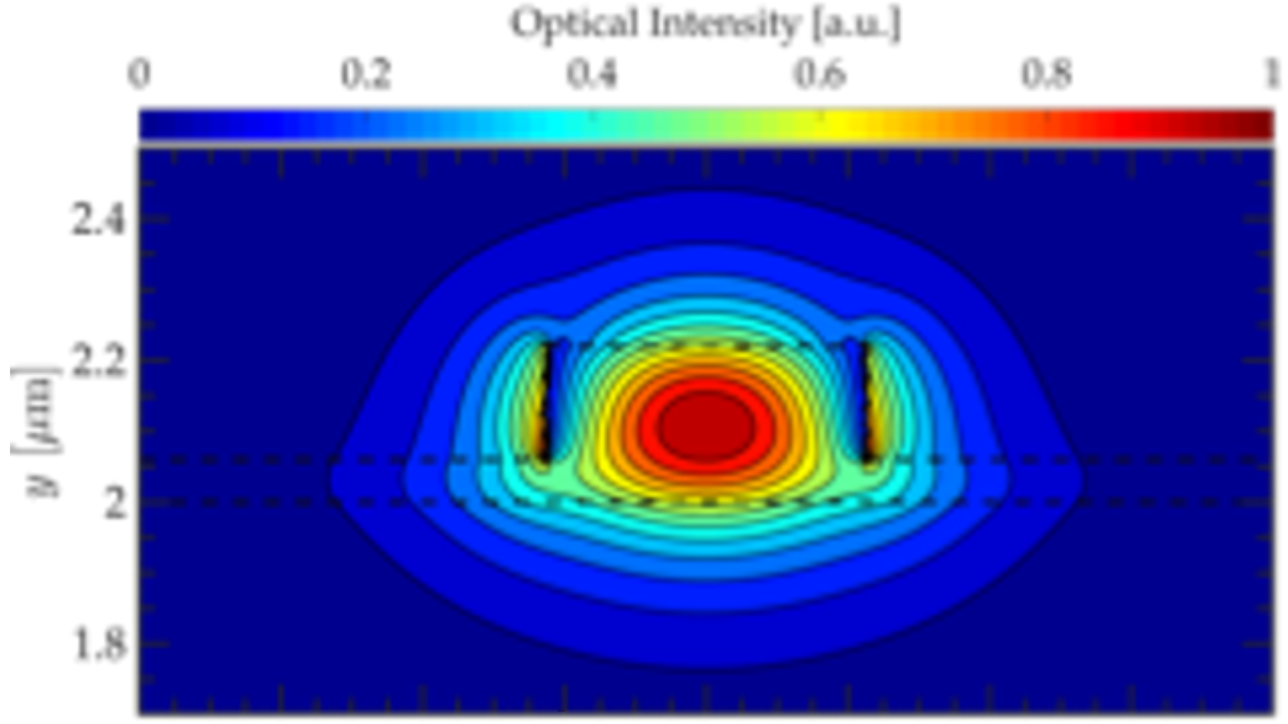




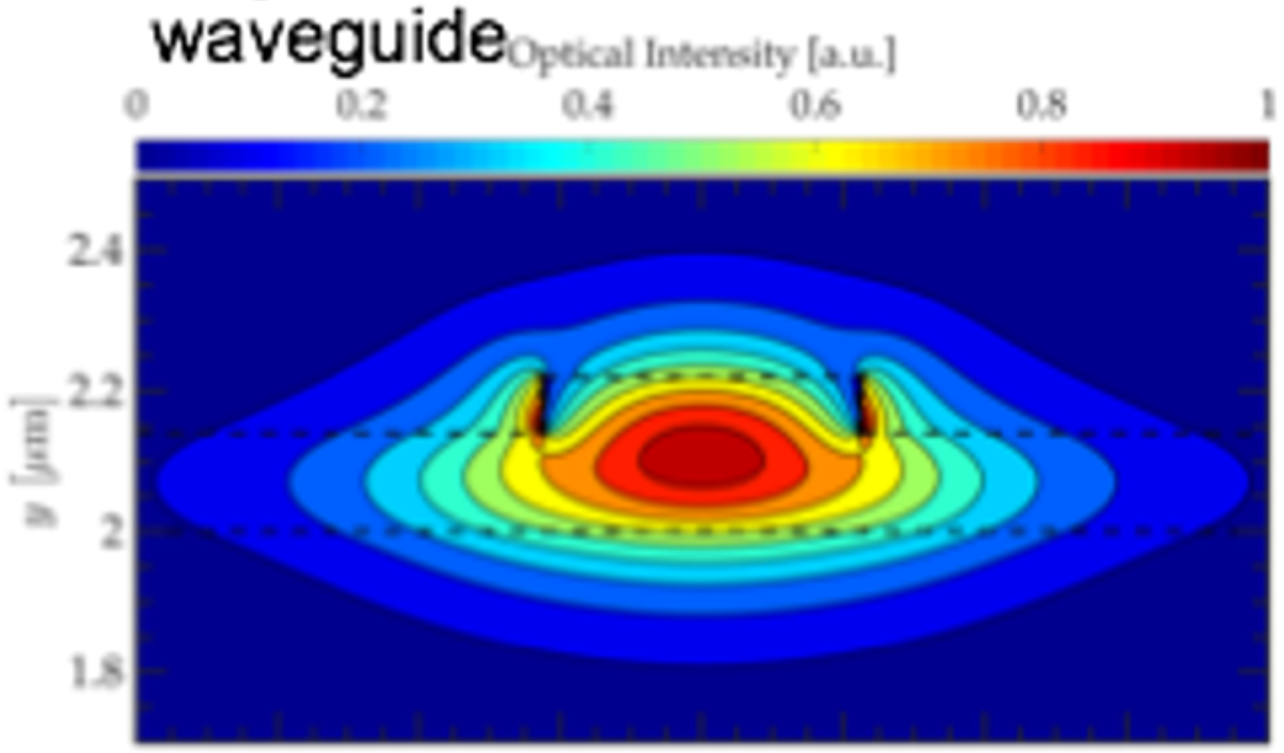
(c) deep etch rib waveguide

(d) shallow etch rib waveguide

TE_0 – **deep-etch rib** waveguide

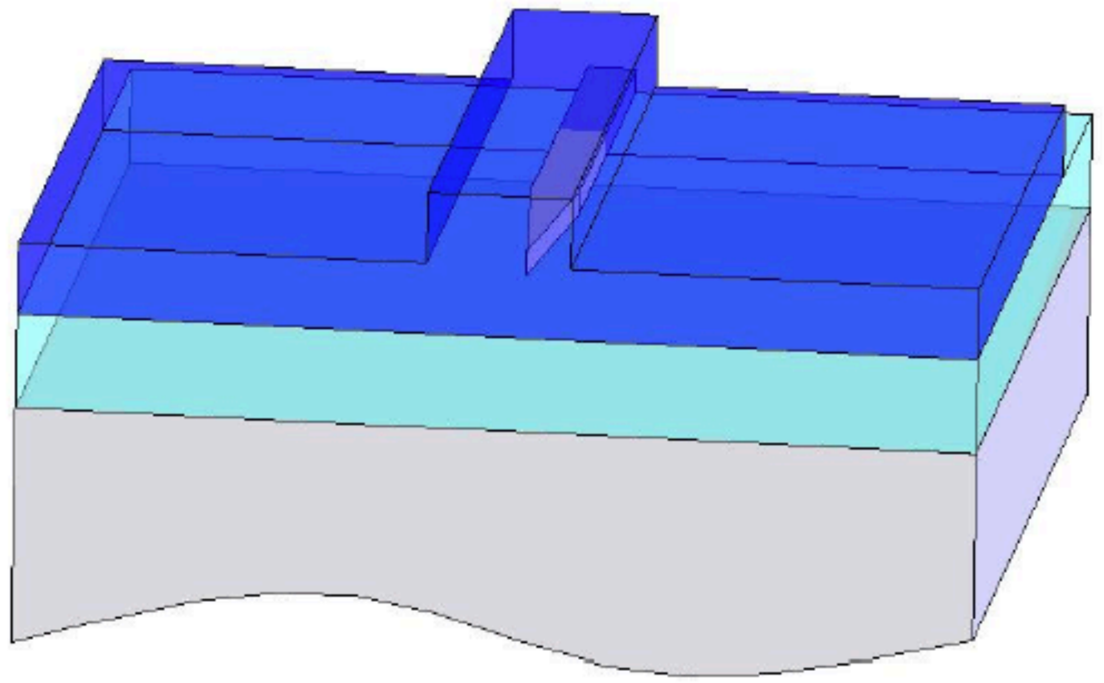


TE_0 – **shallow-etch rib** waveguide



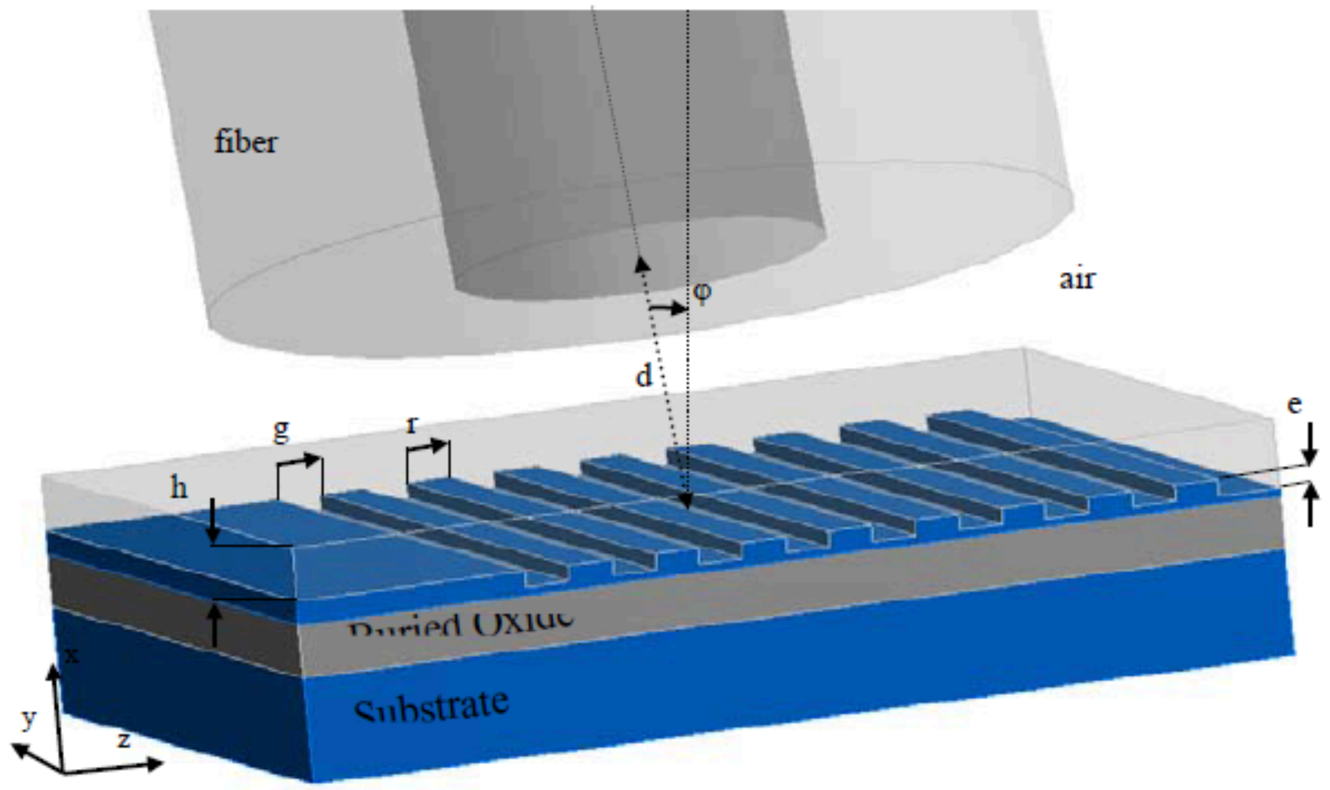
Process devices
Coupling

Lateral coupling

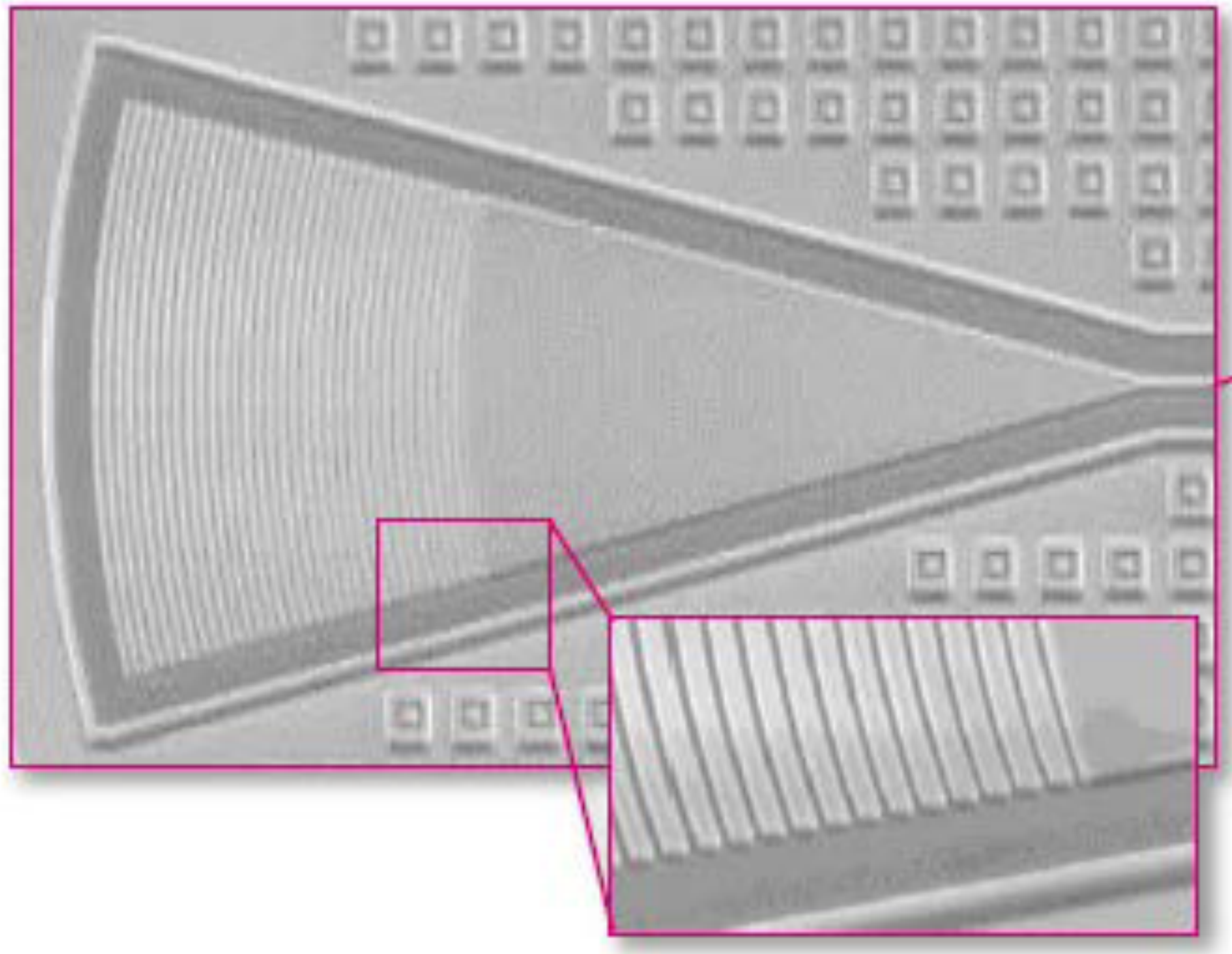


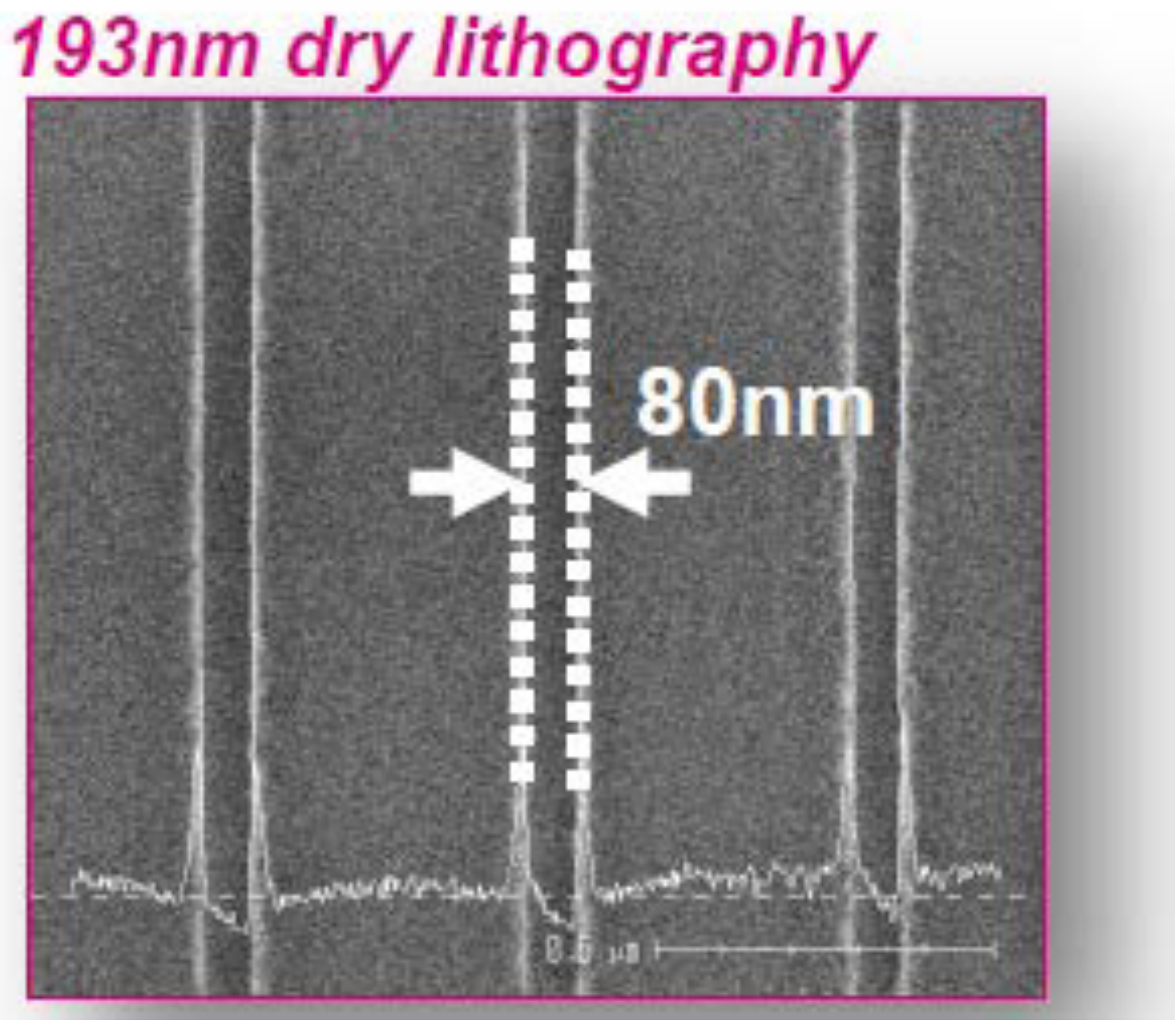
- typically based on inverted tapers
- spotsize: ~3 µm

Vertical coupling



- typically based on gratings
- spotsize: ~ 10 µm





Phase modulation

Plasma dispersion

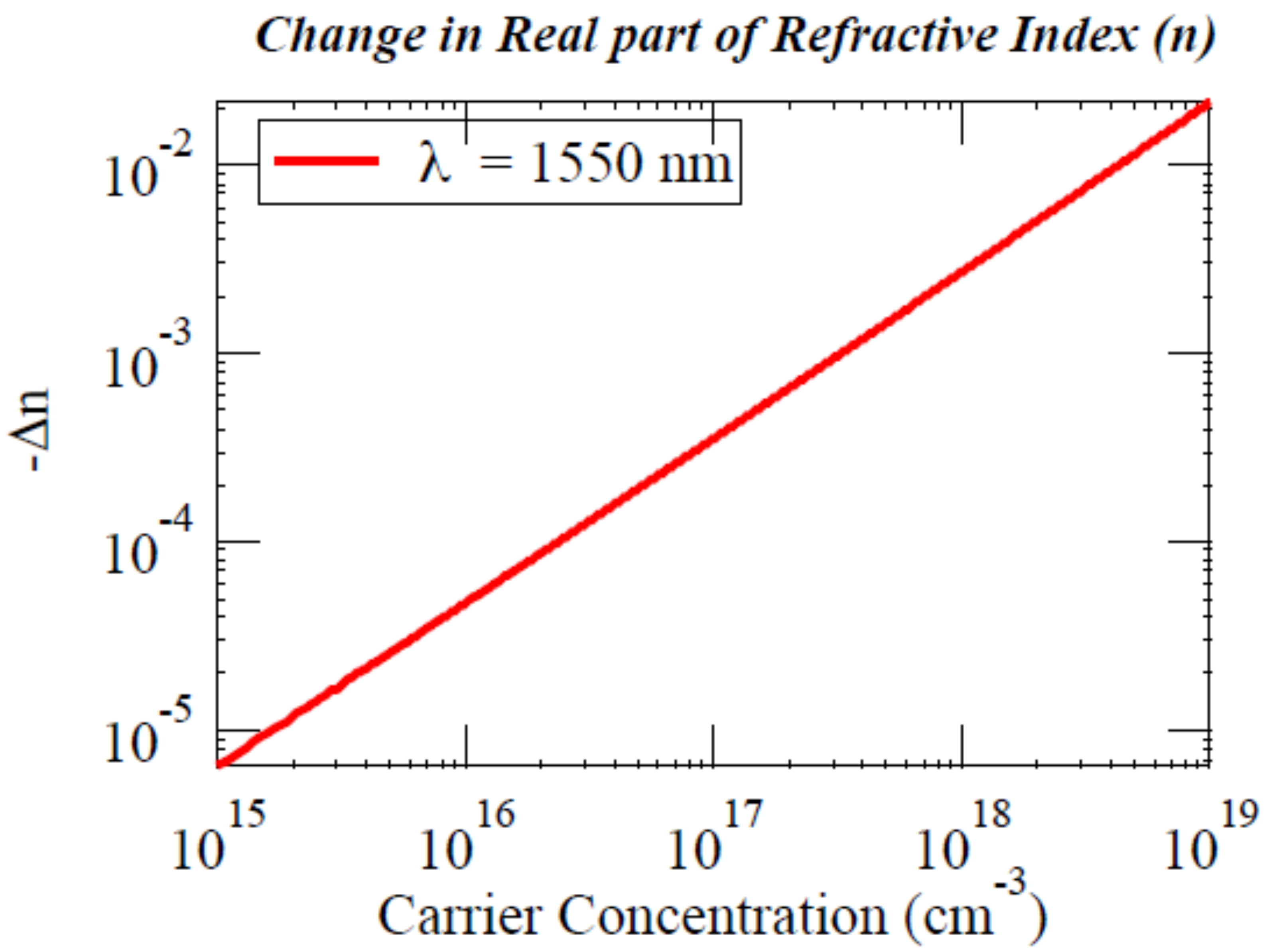
Soref and Bennet equations for telecommunication wavelengths

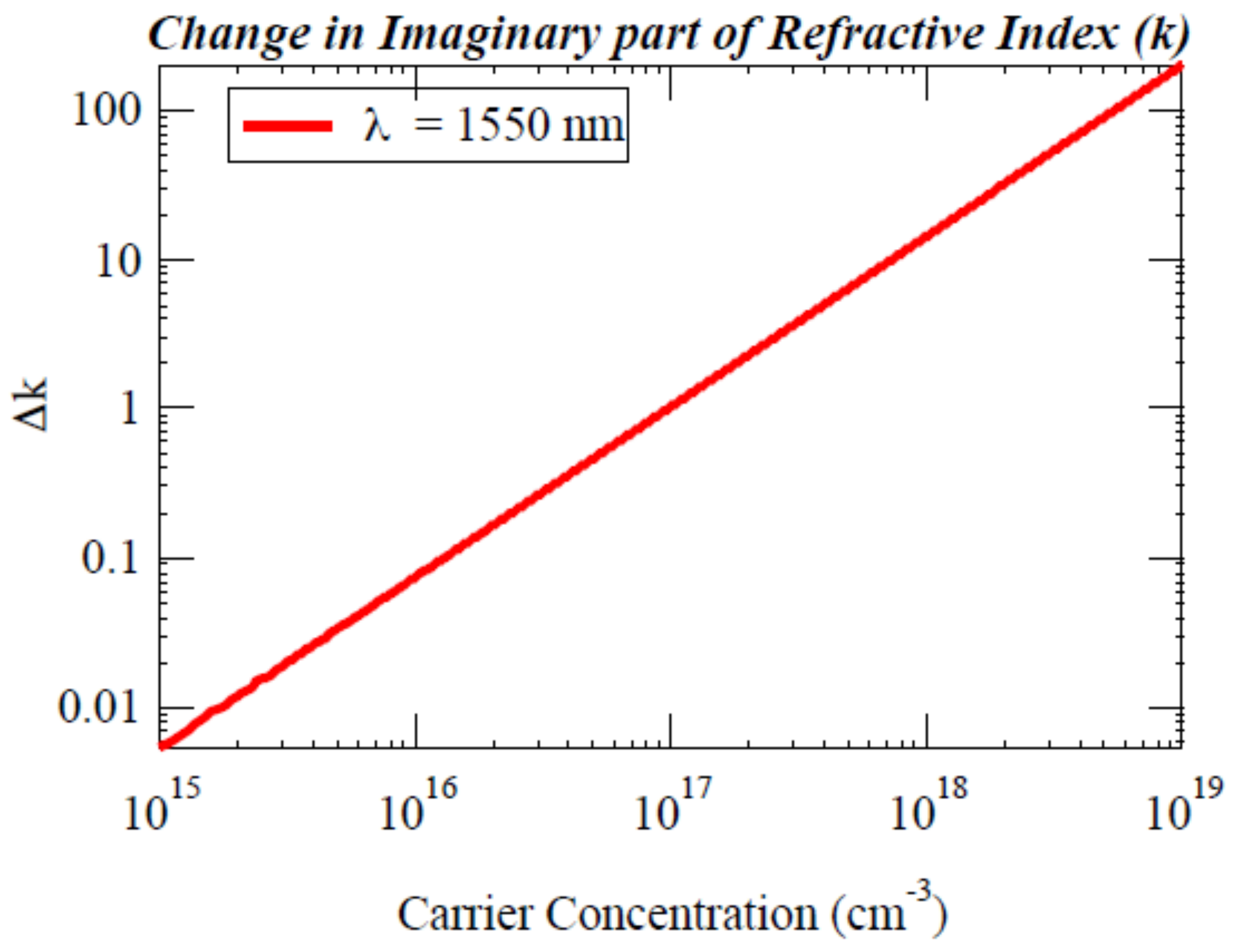
$$\Delta n = -8.8 \cdot 10^{-22} \Delta N_e - 8.5 \cdot 10^{-18} (\Delta N_h)^{0.8}$$

$$\Delta \alpha = 8.5 \cdot 10^{-18} \Delta N_e + 6.0 \cdot 10^{-18} \Delta N_h.$$

Changes in the free carrier concentration in a semiconductor are described by the Plasma Dispersion Effect.

The change of real and imaginary parts of the refractive index in Silicon occurs by changing the carrier concentrations (Drude Lorenz equations)

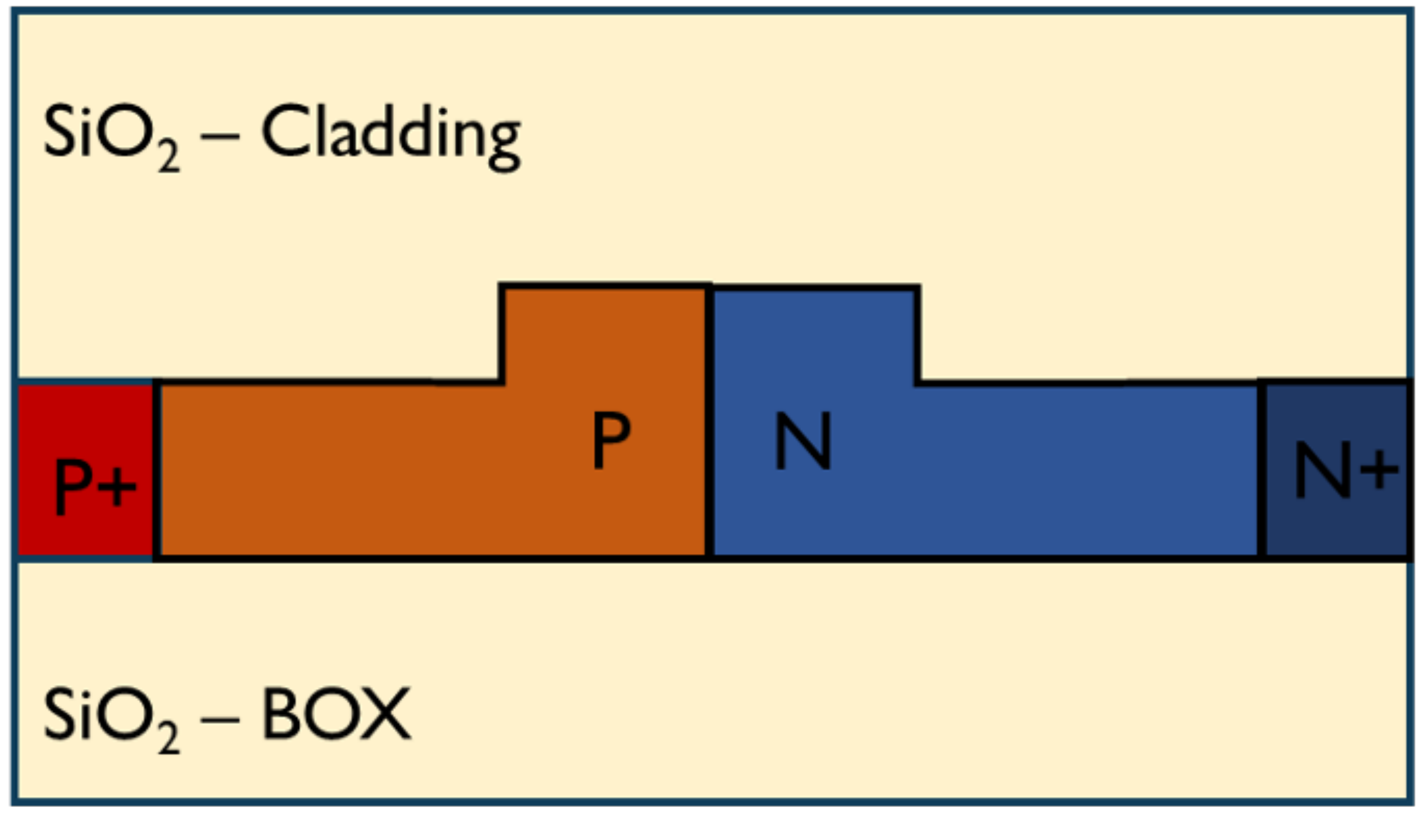


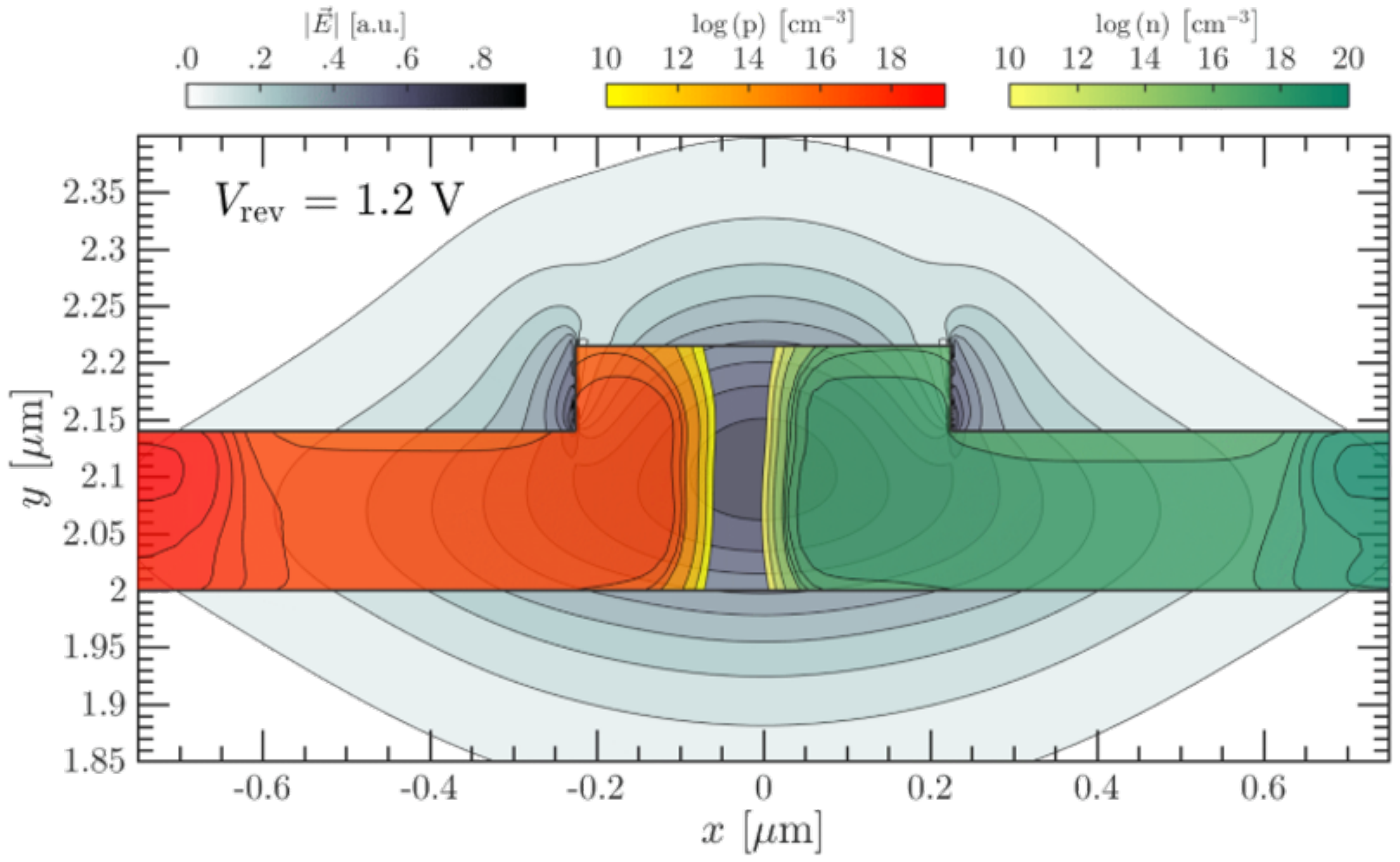


Silicon Photonics devices have typically 10^{18} cm^{-3} doping concentrations

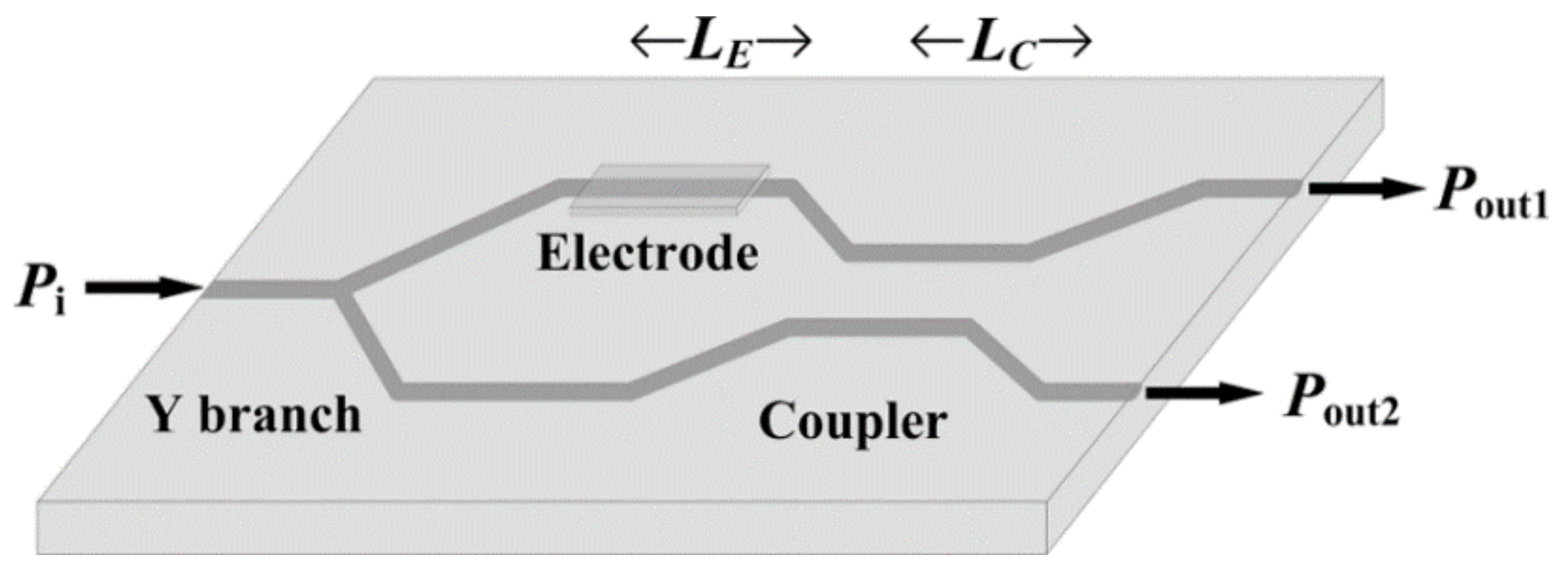
Principle of operation

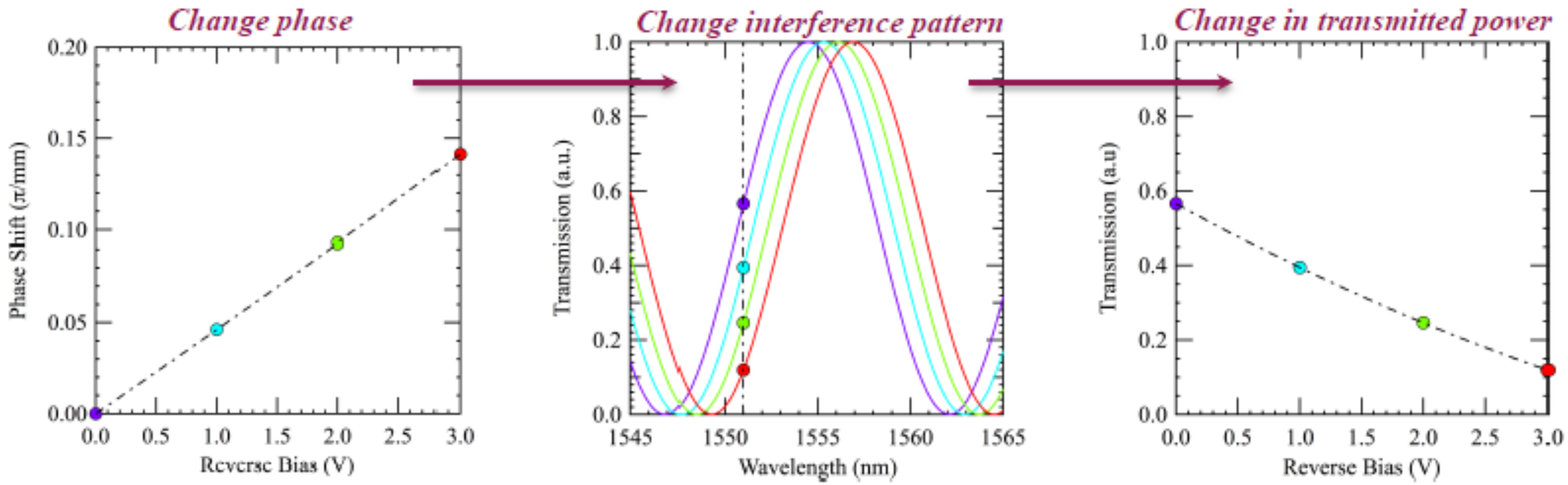
- **PN-junction embedded in SOI waveguide**
- **Depletion-driving for high-speed operation**
- **Optical phase modulation**





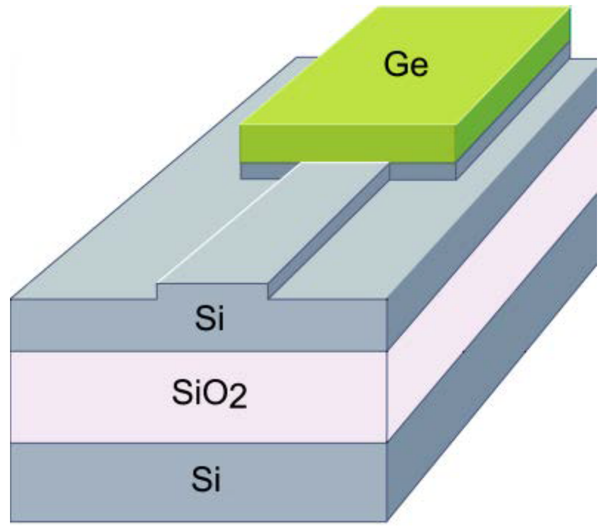
Principle of operation



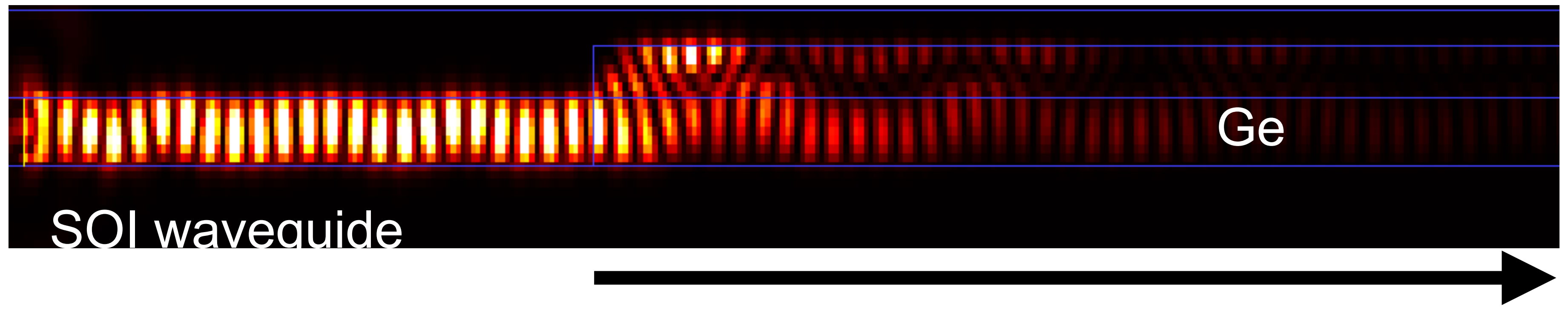


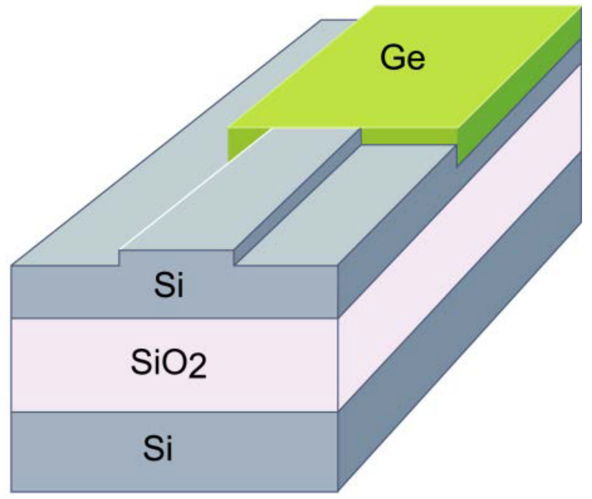
Detection

- **Germanium**
  - High absorption coefficient $\alpha \approx 9000\ cm^{-1}$ at 1.3 µm (3.3 µm 95%)
  - Low capacitance devices, and high frequency
  - However lattice misfit with Silicon (specific growth strategies required) and high dark current (low indirect bandgap)

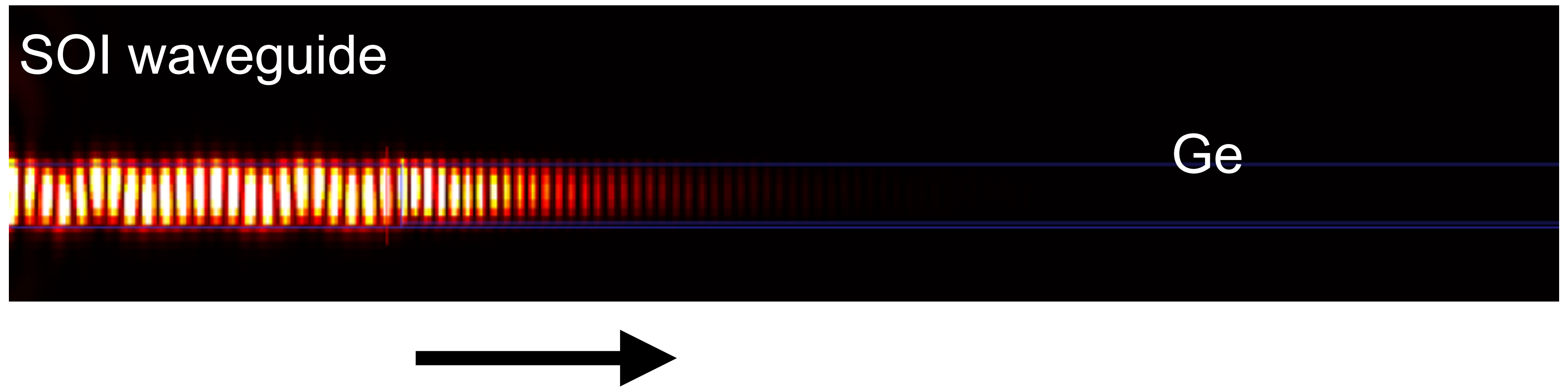


Vertical coupling





Butt coupling



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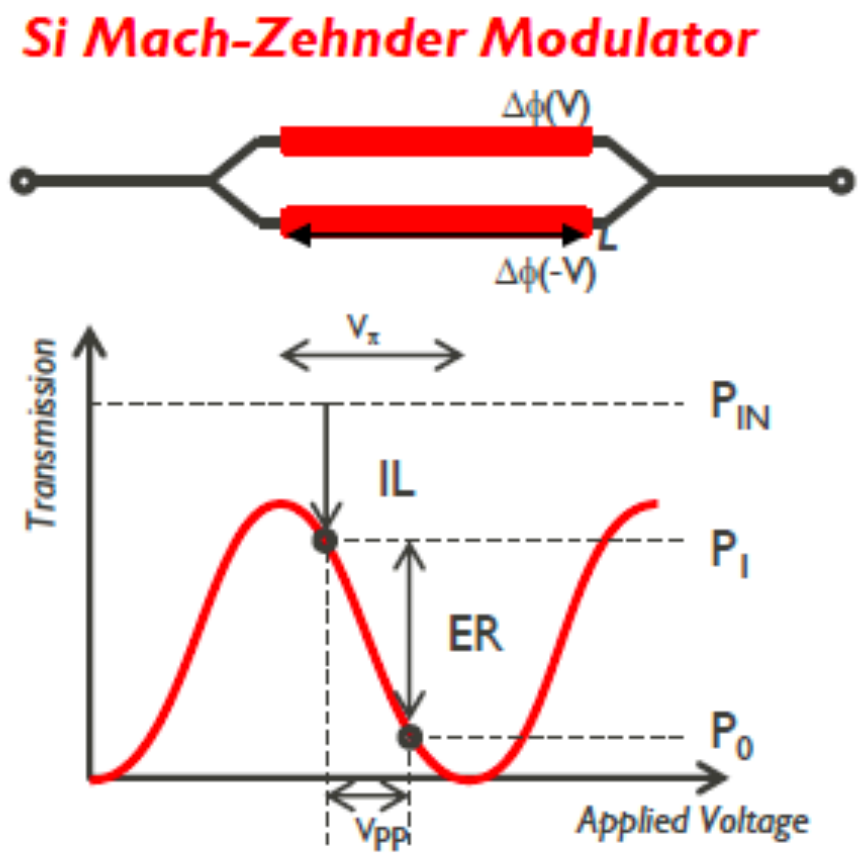
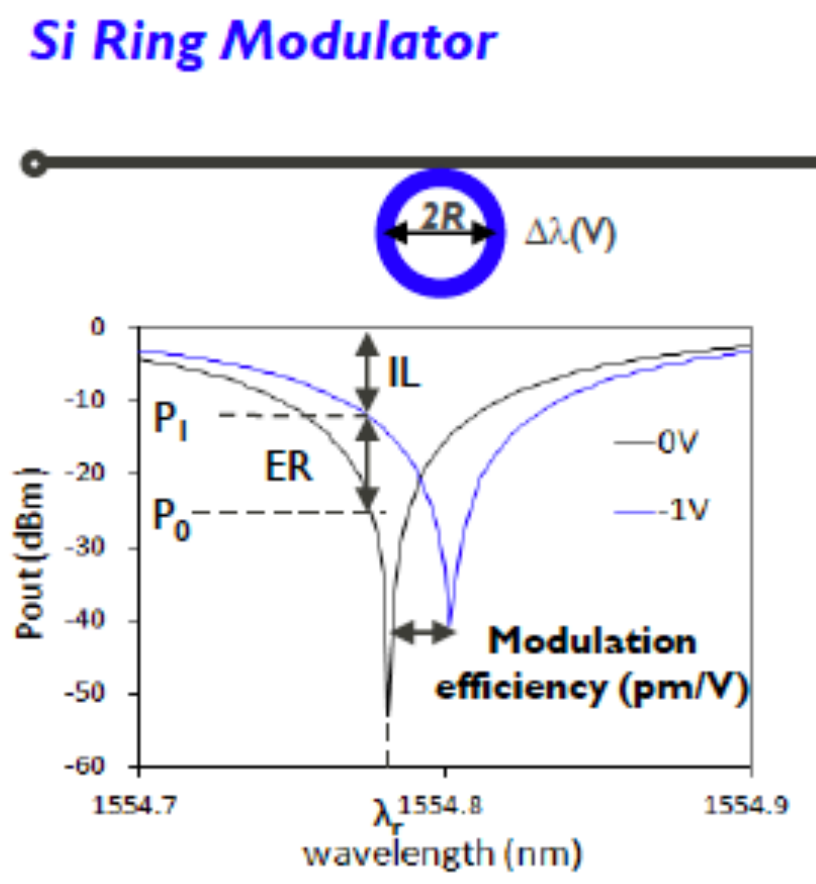
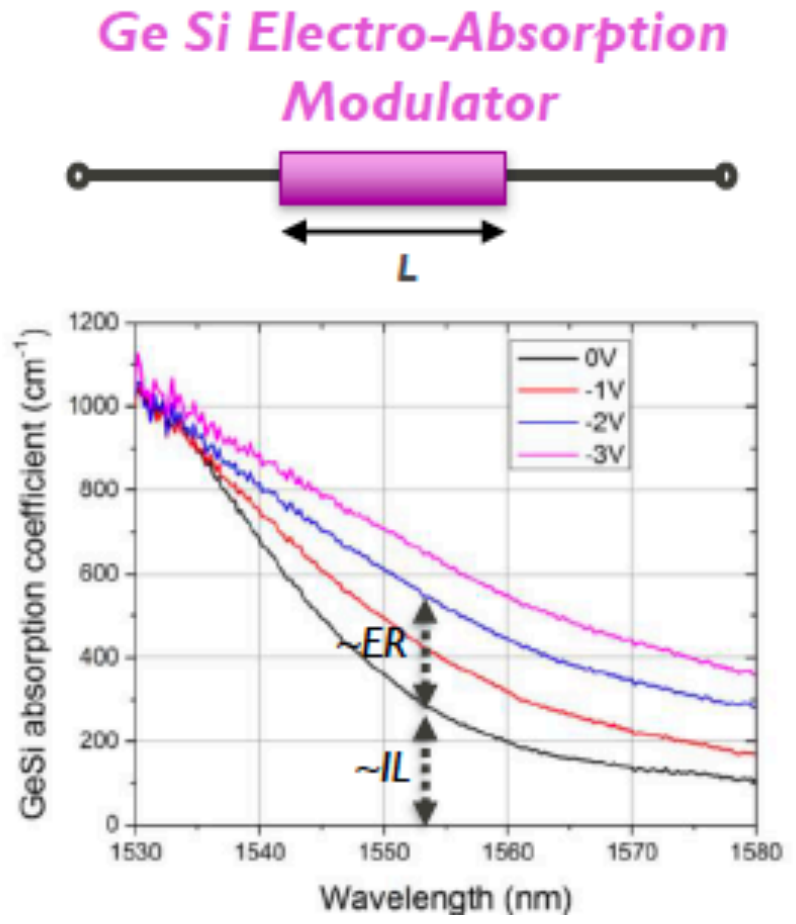
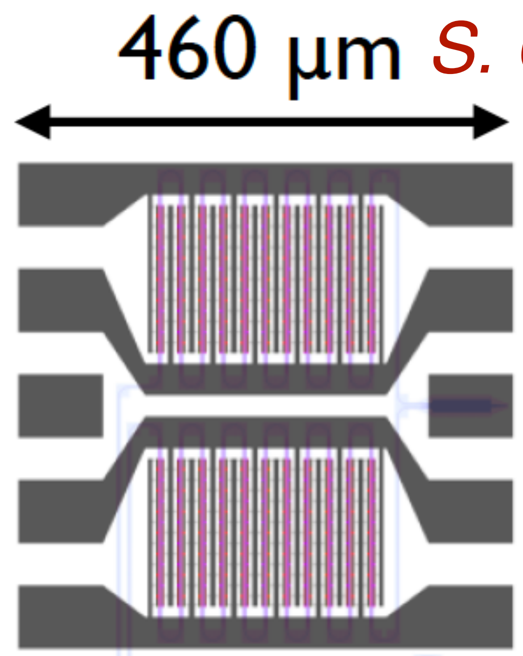
Silicon Photonics modu



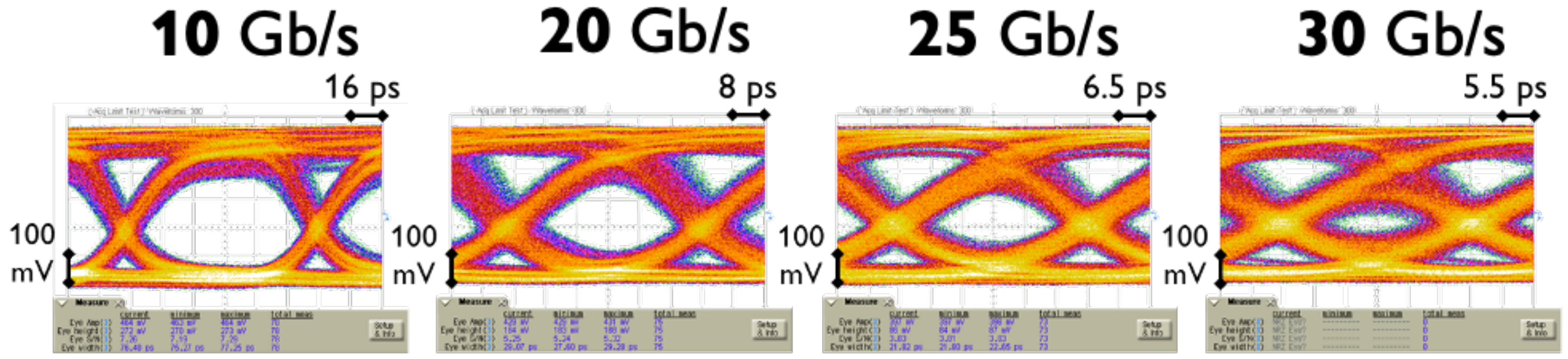


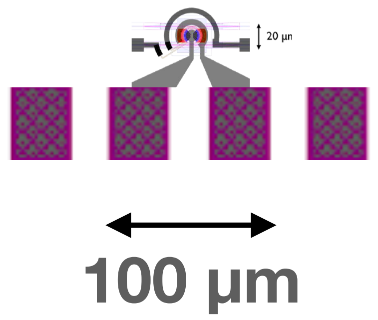


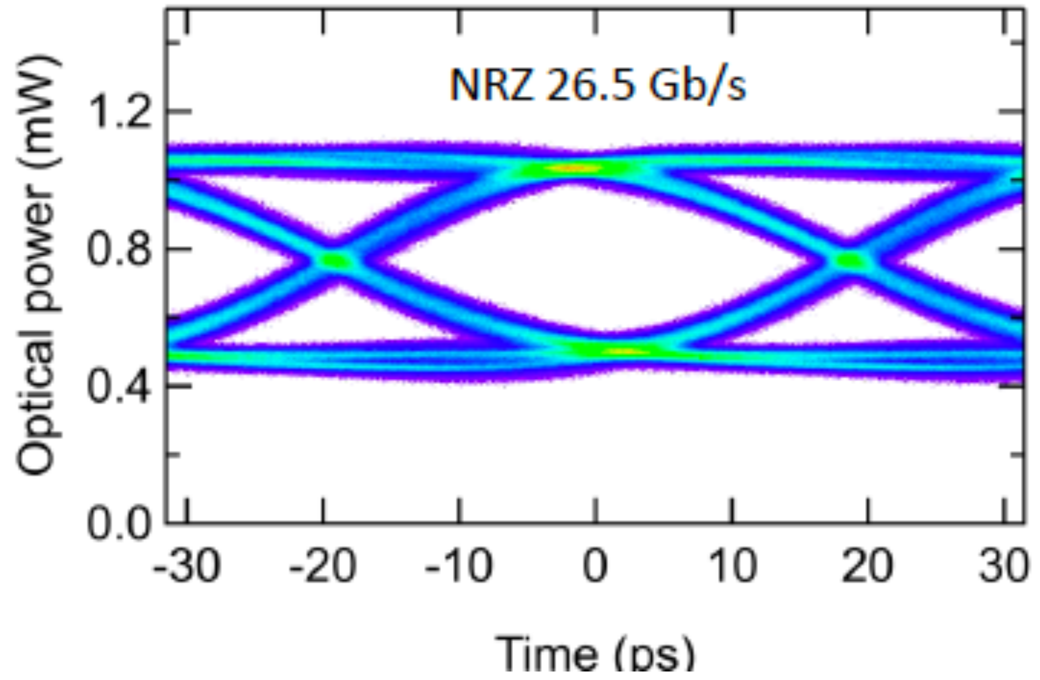
- **Mach-Zehnder Modulator (MZM)**
  - Temperature insensitive
  - Typically big footprints (~1 mm) and high V_π (2V)
  - Folded MZM have smaller footprint (0.5 mm)
- **Ring Modulators (RM)**
  - Much smaller intrinsically, but pads at 100 µm
  - Low power consumption
  - Temperature sensitive
- **Ge Si Electro-absorption (EA)**
  - More suitable for 1550 nm wavelengths
- **Thin-film LiNb on SOI waveguide**
  - 2 mm long devices driven with 1.4 V reach 40 Gb/s per lane
  - Still in R&D phase but appealing for FCC-hh

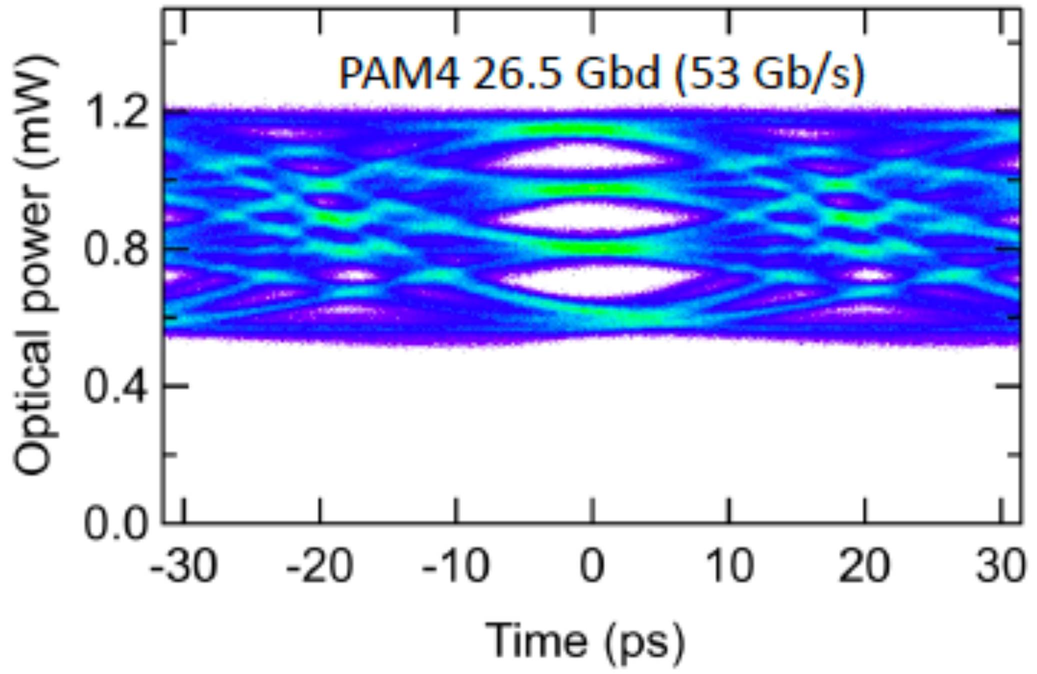


S. Cammarata et al (FALAPHEL) doi: 10.1109/IPC53466.2022.9975756.



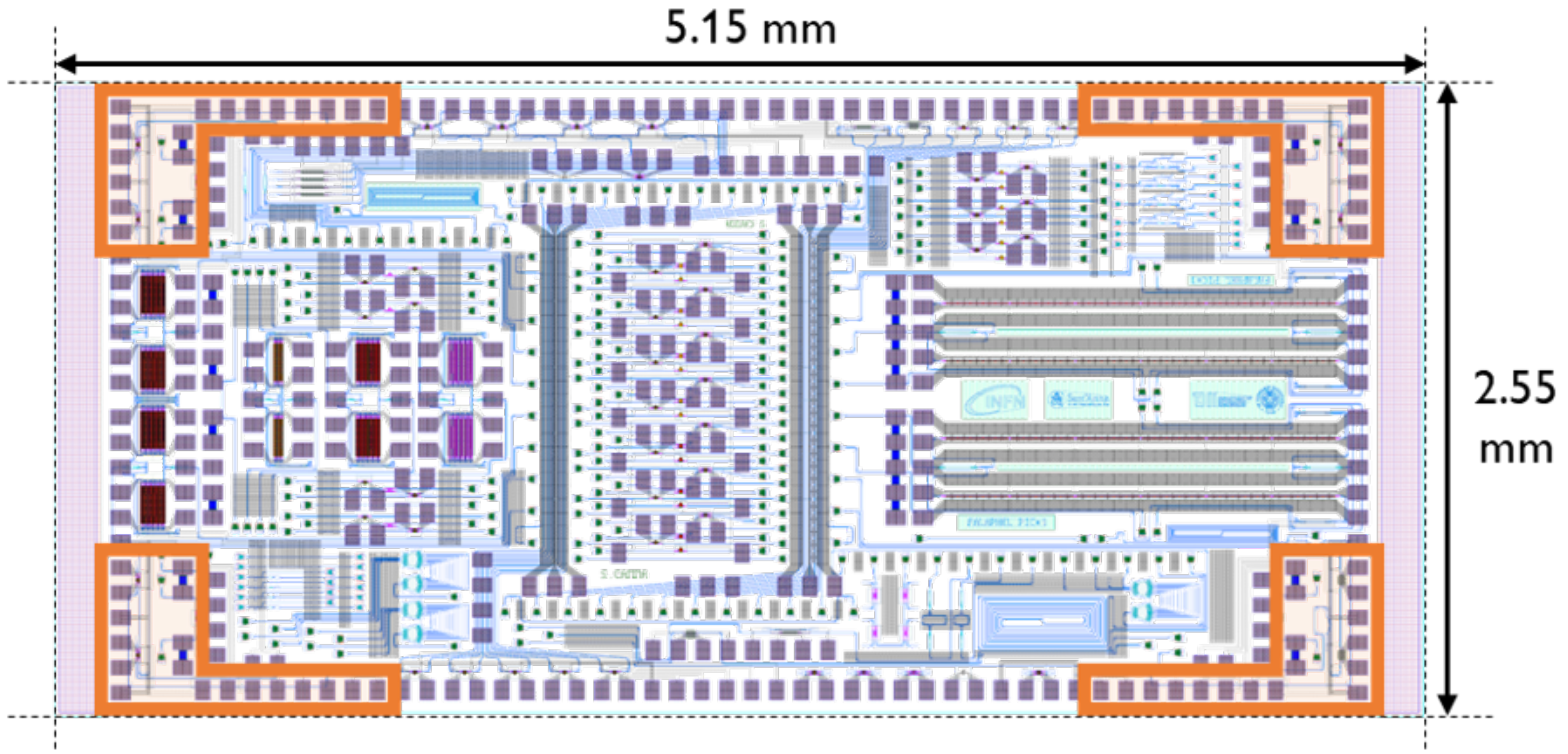




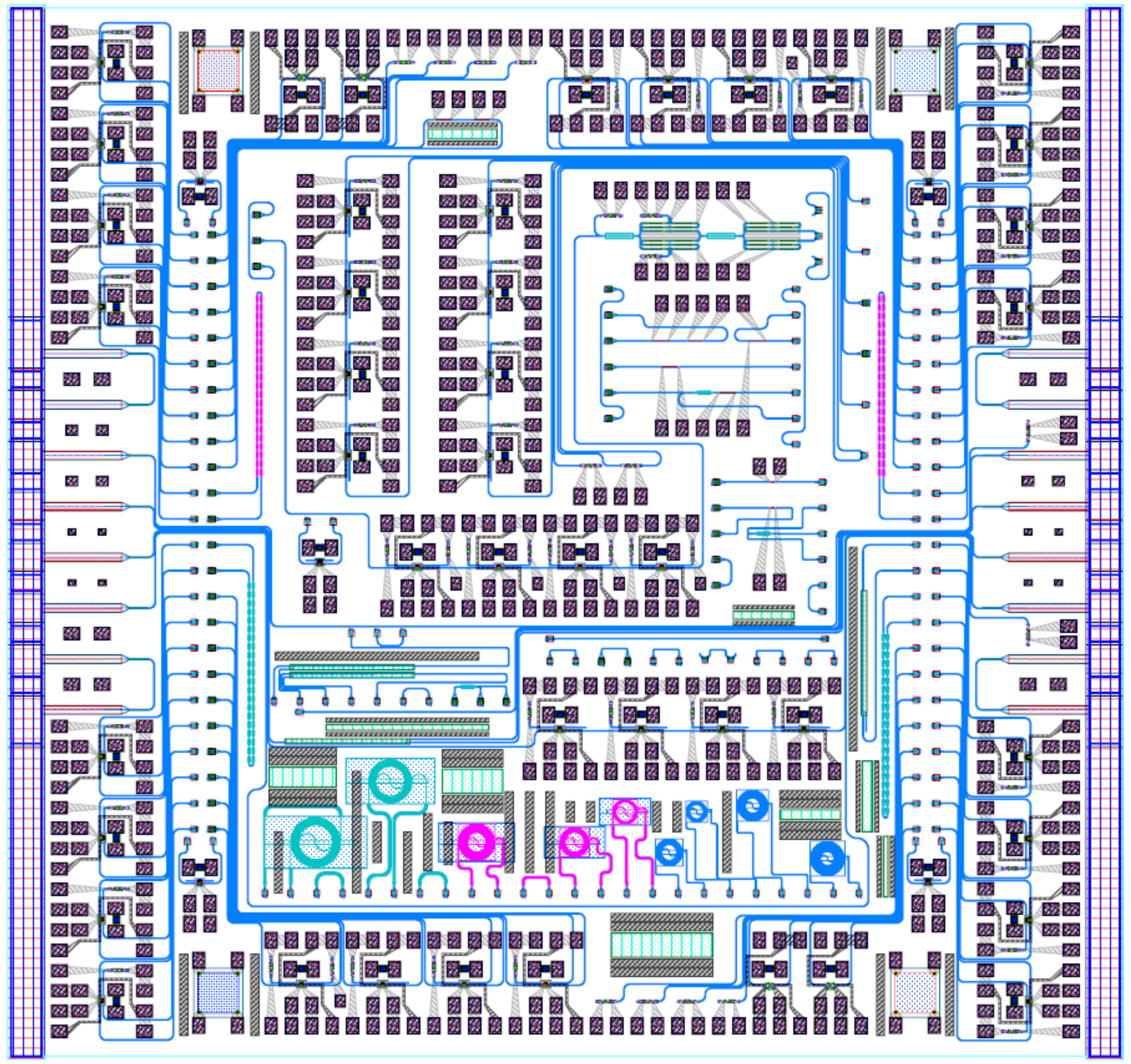


C. Scarcella et al. (CERN) TWEPP2022

Circuit design



INFN FALAPHEL PICV2 (ISIPP50G) - 2.5x 5 mm2 submitted Oct 2022
CWDM (2xRM) C-band



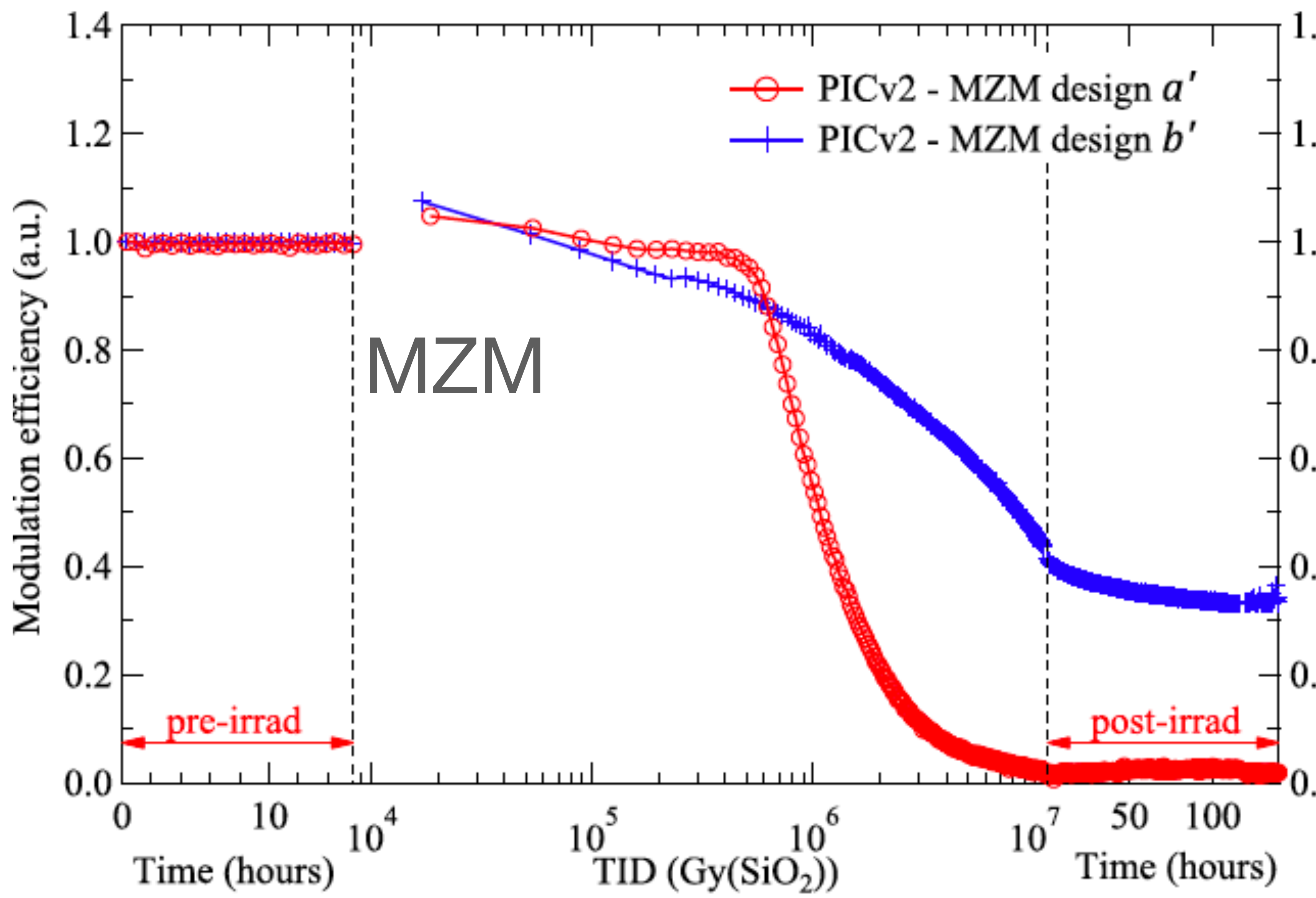
CERN PICV3 (ISIPP50G) - 5x 5 mm2 submitted Oct 2022
CWDM (4x) both O-band and C-band

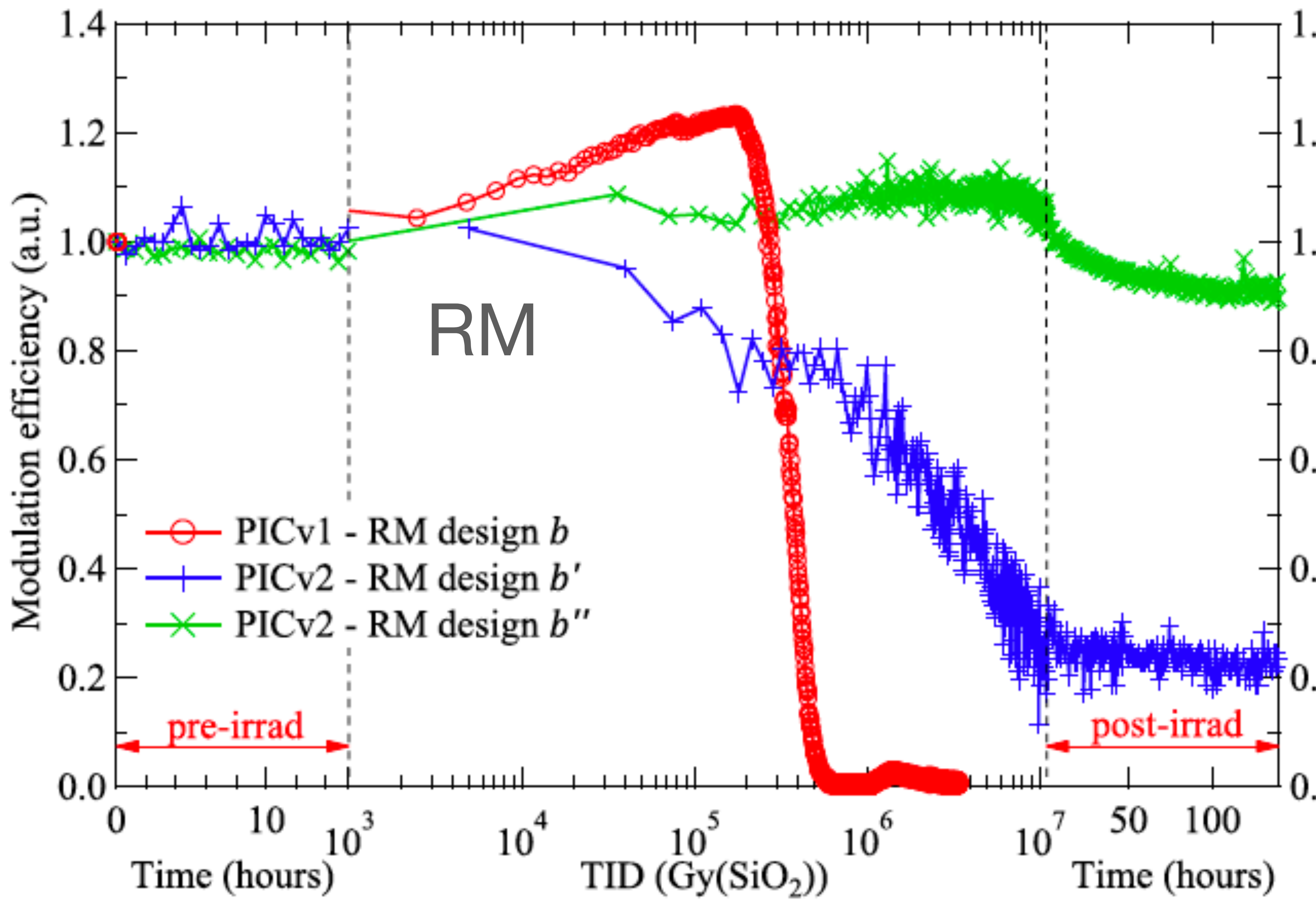
M. Lalović et al., doi: 10.1109/TNS.2022.3148579.

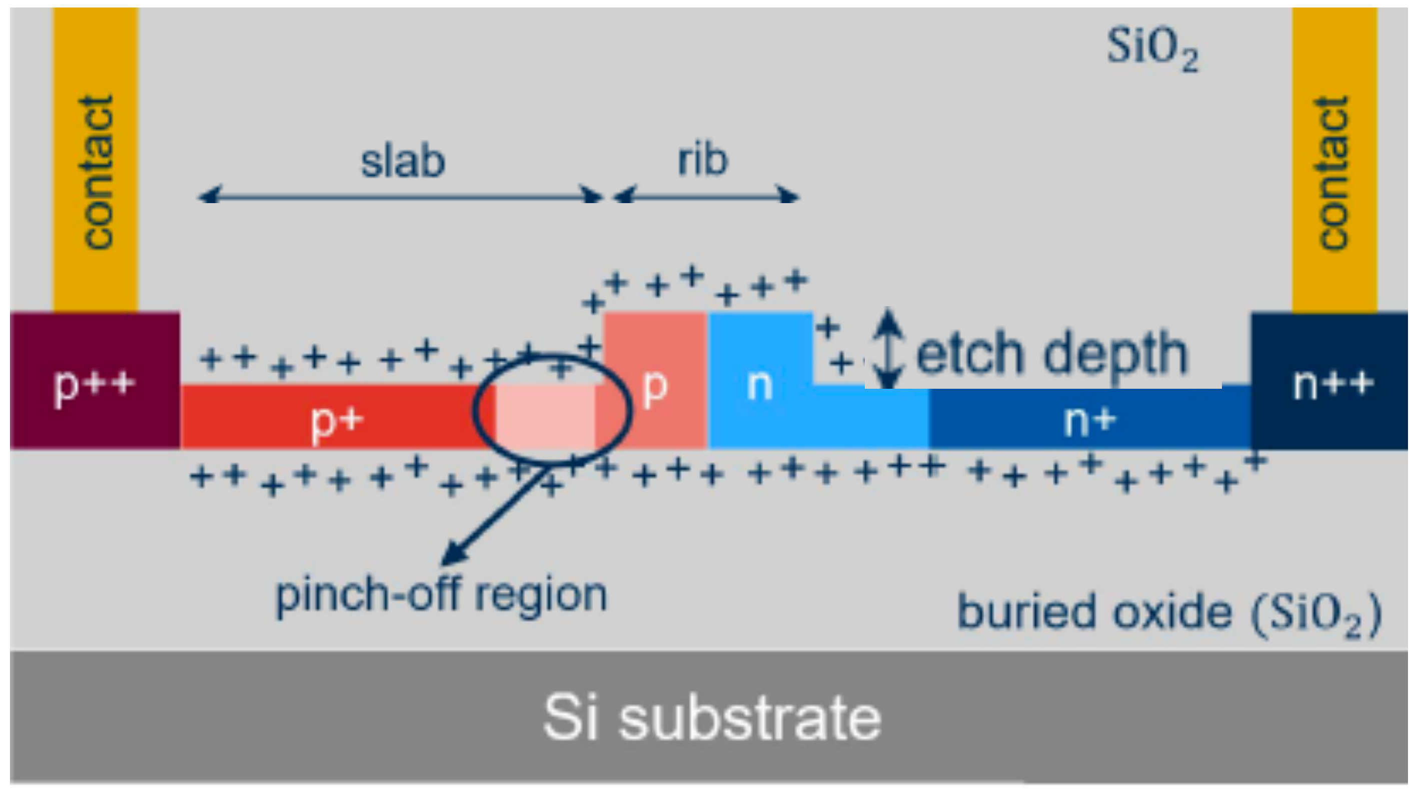
Silicon Photonics

Radiation tolerance

- Process and design dependence:
  - Loss of modulation caused by pinch-off effects of holes in the p-doped region
  - Higher doping concentrations or thicker etch depth allow more radiation resistance
  - Similar behaviour for RM and MZM
- Single-Event Effects devices started to be detected





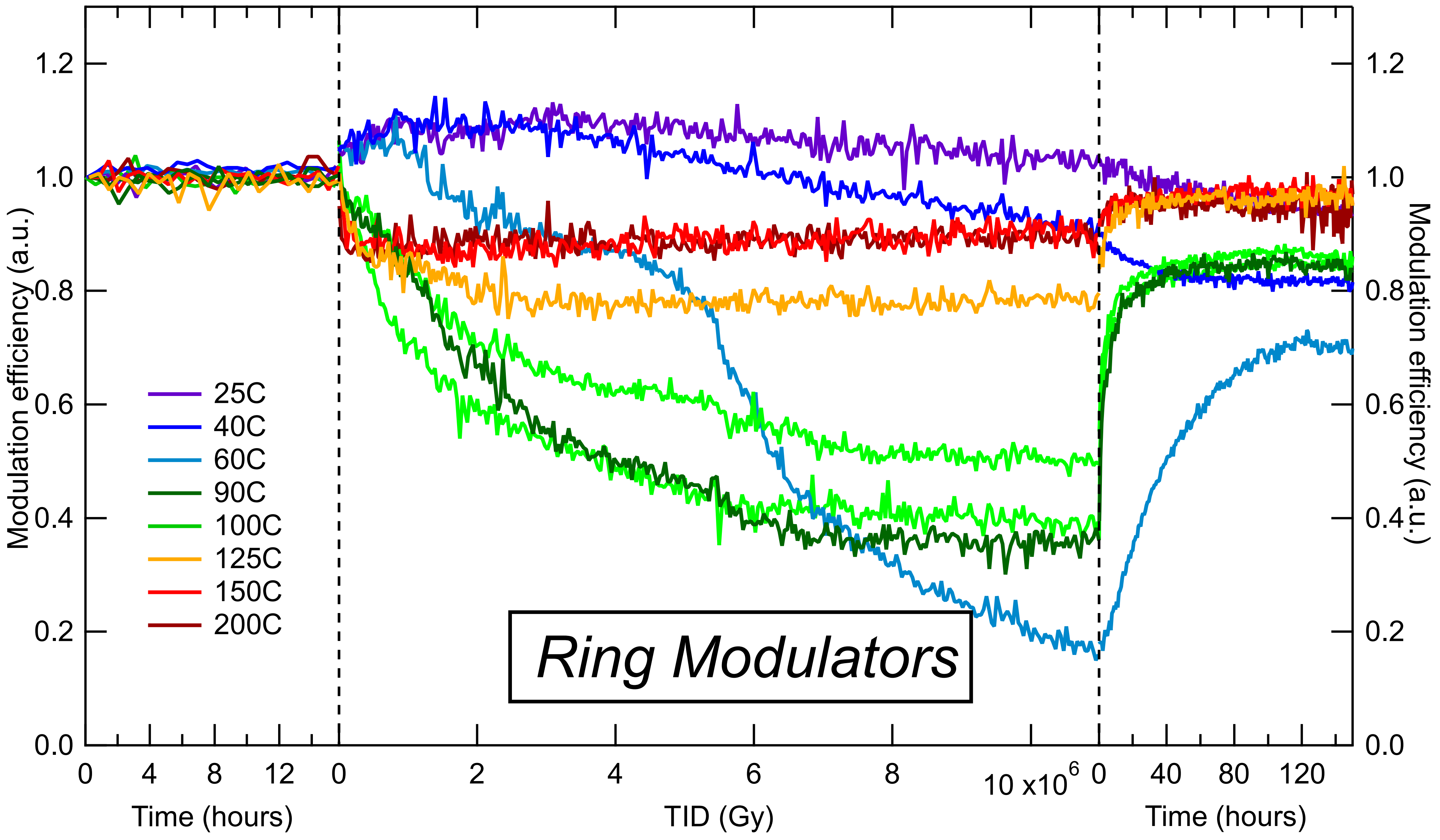


Silicon Photonics

Radiation tolerance

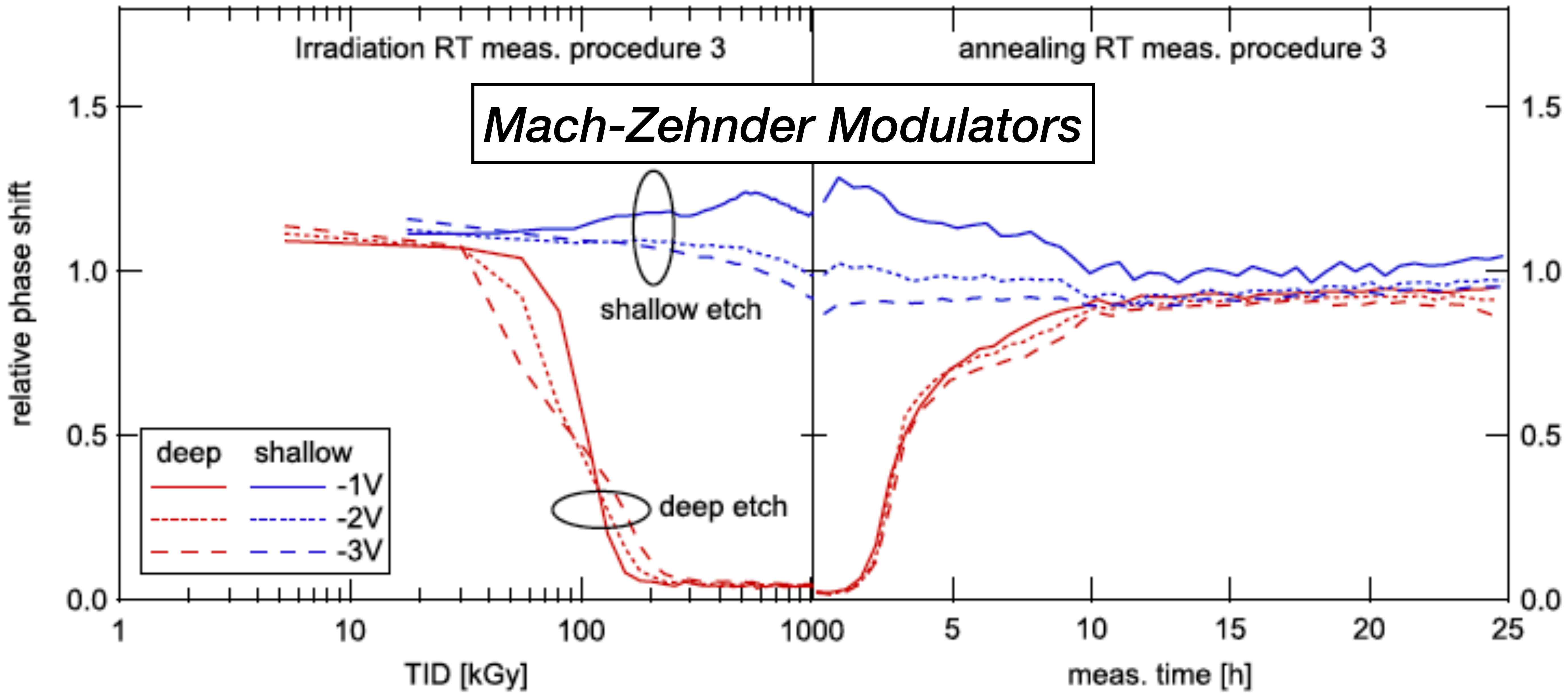
- CERN carried out X-ray & neutron irradiation tests
  - Neutron irradiation less damaging, independent of temperature
  - TID potentially more damaging, can be fully annealed with elevated temperature using on-chip heaters or reverse bias. Some effects due to temperature to be considered

M. Lalović et al., doi: 10.1109/TNS.2022.3148579.



> 10 MGy

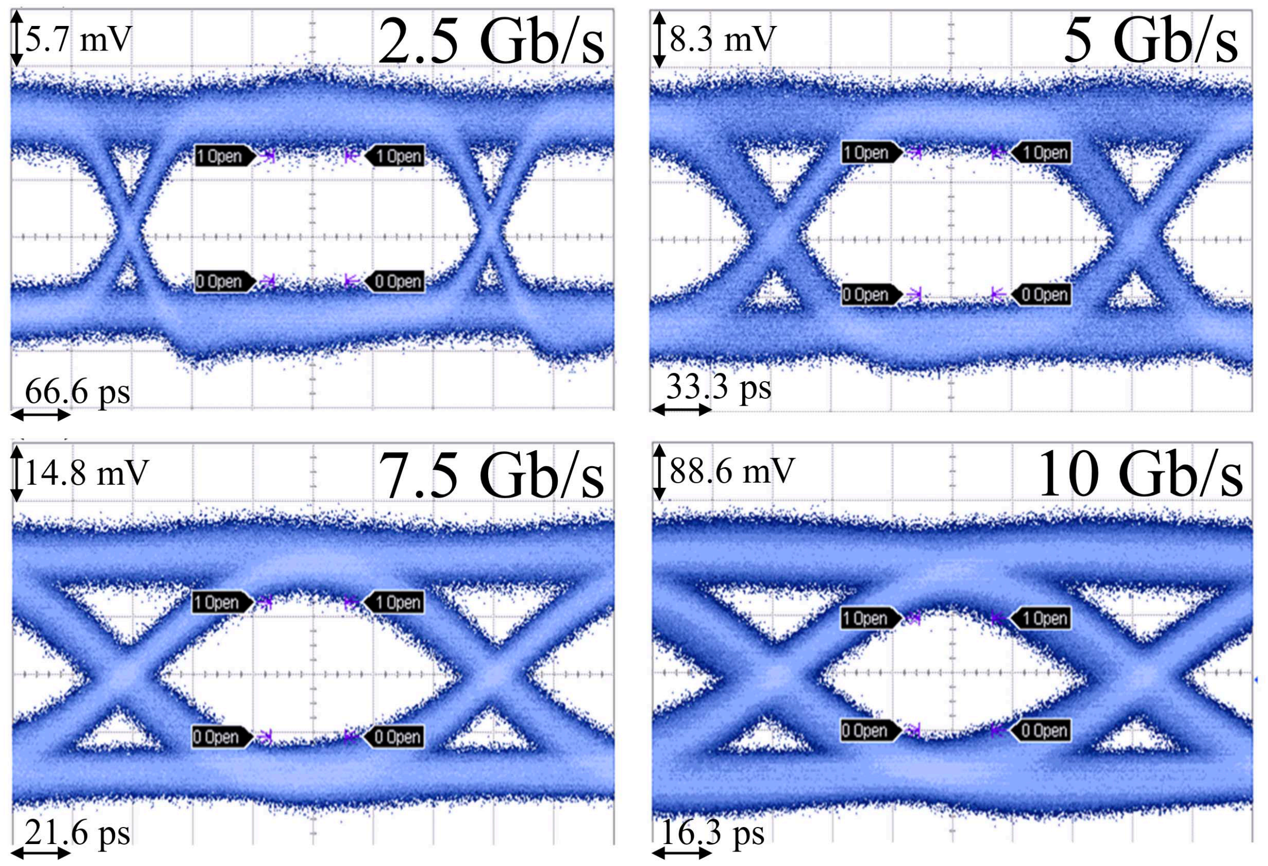
A. Kraxner et al., doi: 10.1109/TNS.2018.2823863.

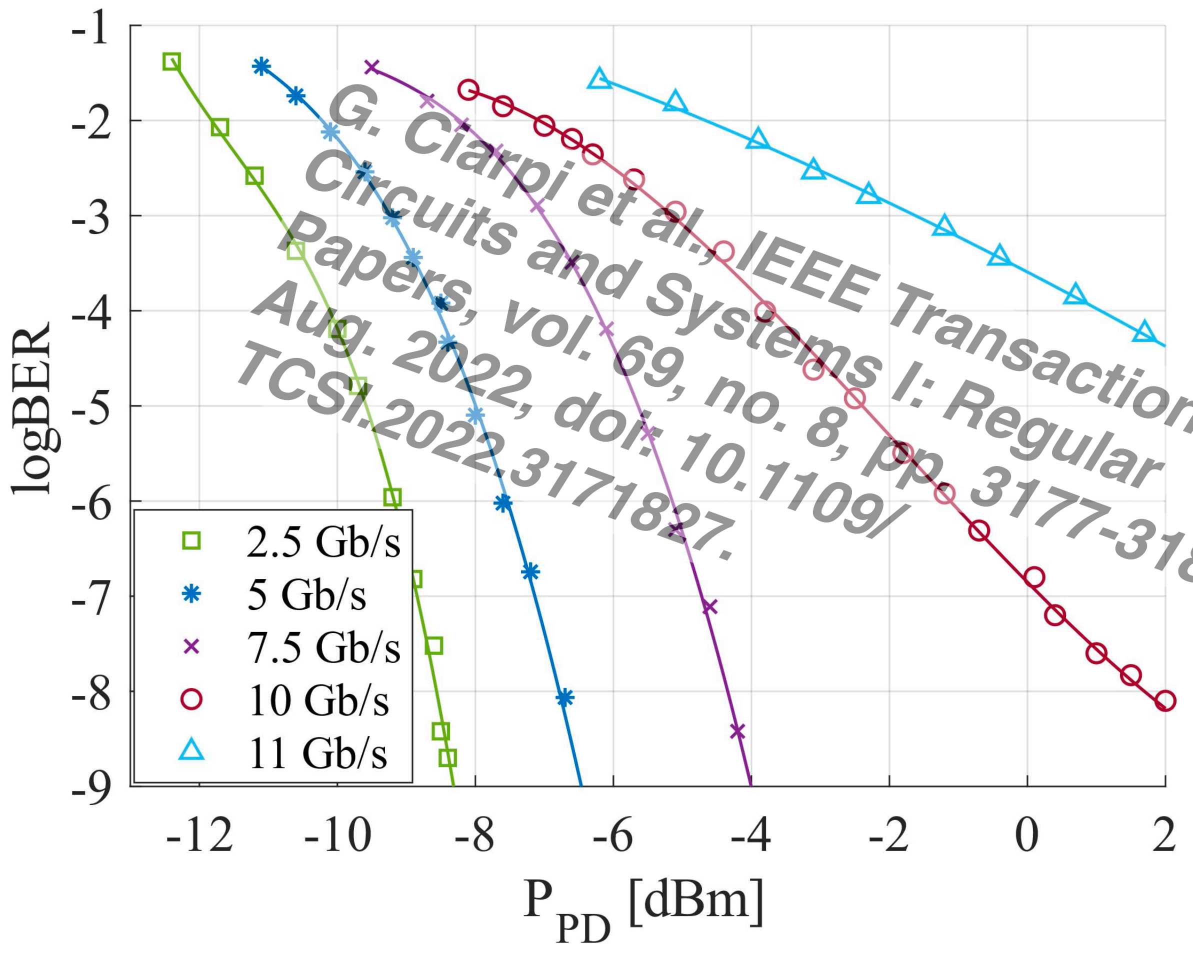


Silicon Photonics: integration with electric drivers

HEP state of the art

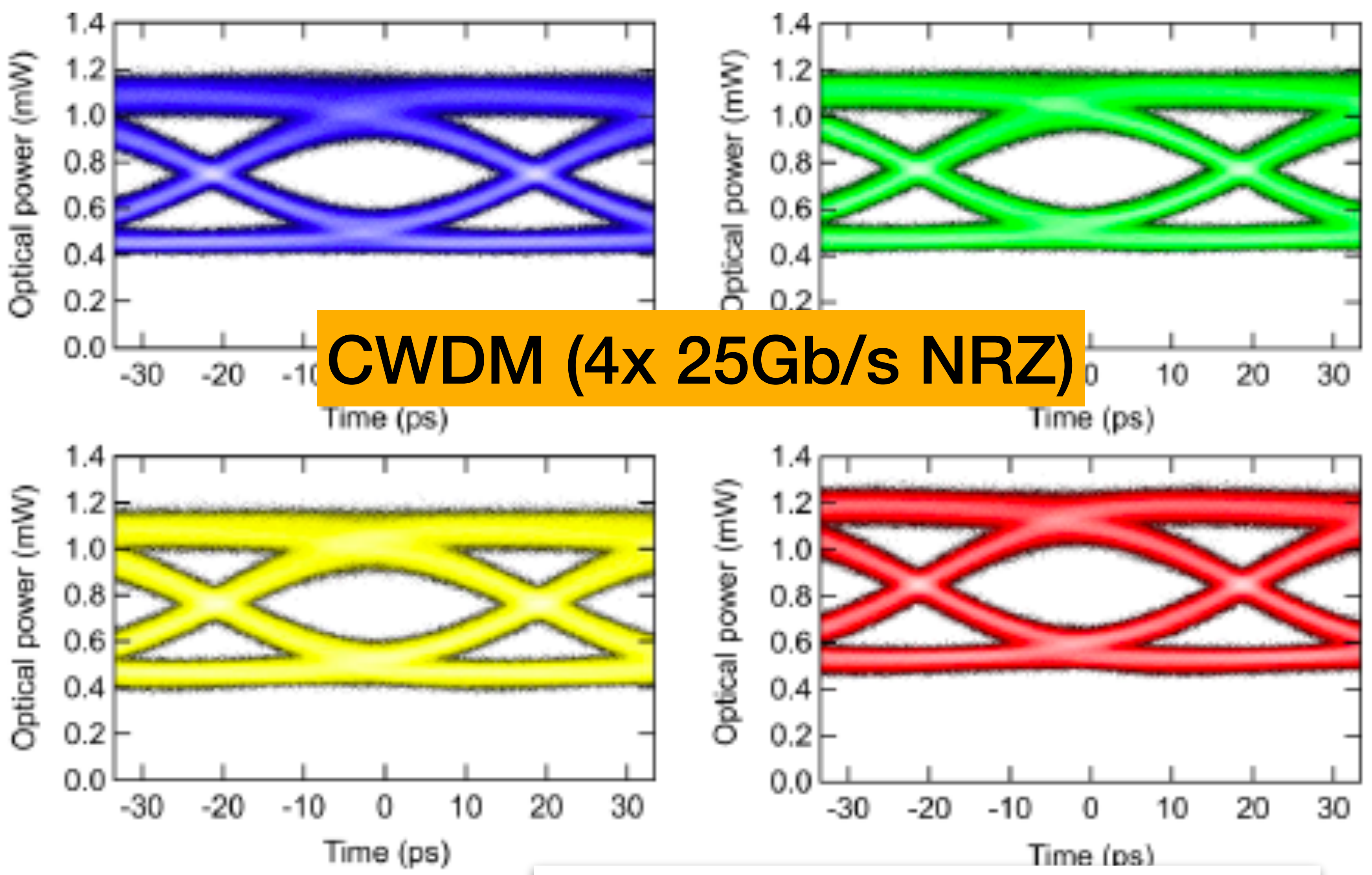
- CERN PIC (MZM - IMEC iSIPP25G) wire bonded to INFN PHOS4BRAIN rad-hard driver (65 nm)





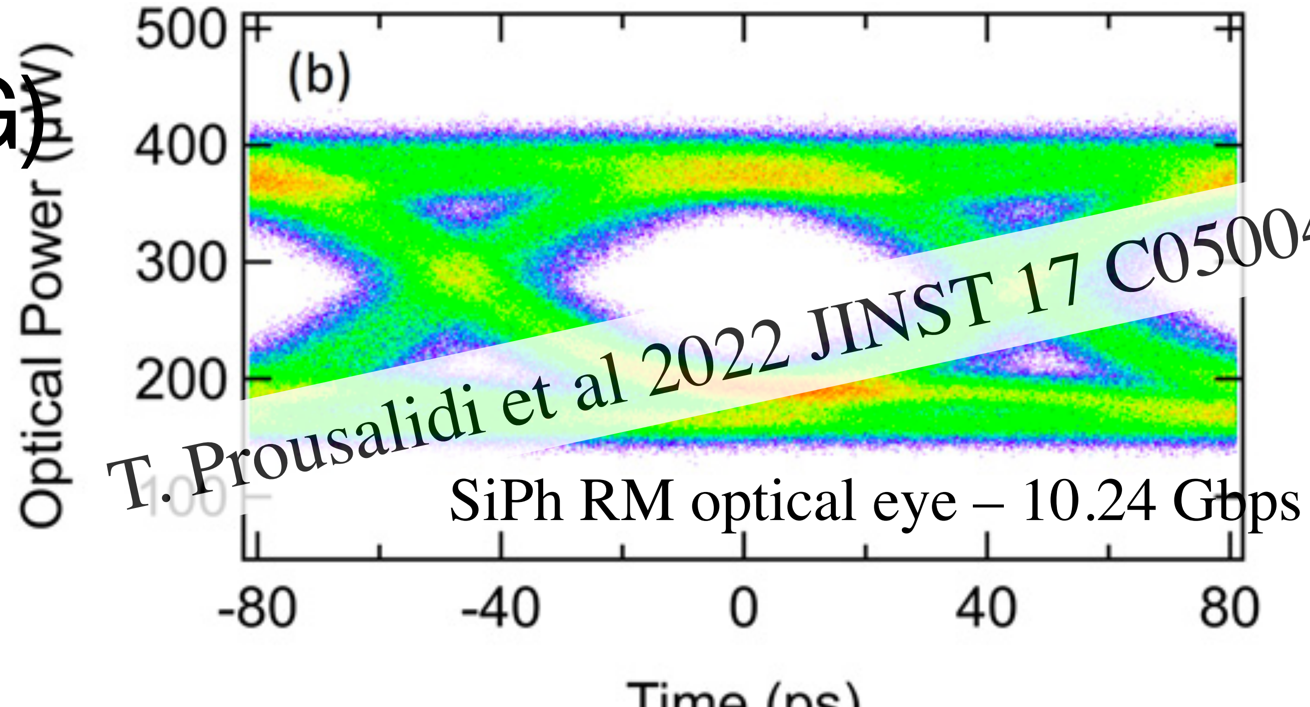
G. Ciarpi et al., IEEE Transactions on Circuits and Systems I: Regular Papers, vol. 69, no. 8, pp. 3177-3189, Aug. 2022, doi: 10.1109/TCSI.2022.3171827.

- CERN PIC (RM - IMEC iSIPP50G) wirebonded to commercial driver (CWDM demo)



C. Scarcella et al - TWEPP 2022

- CERN PIC (RM - IMEC iSIPP50G) wirebonded to LpGBT (65 nm)



SiPh RM optical eye – 10.24 Gbps

T.Prousalidi et al 2022 JINST 17 C05004

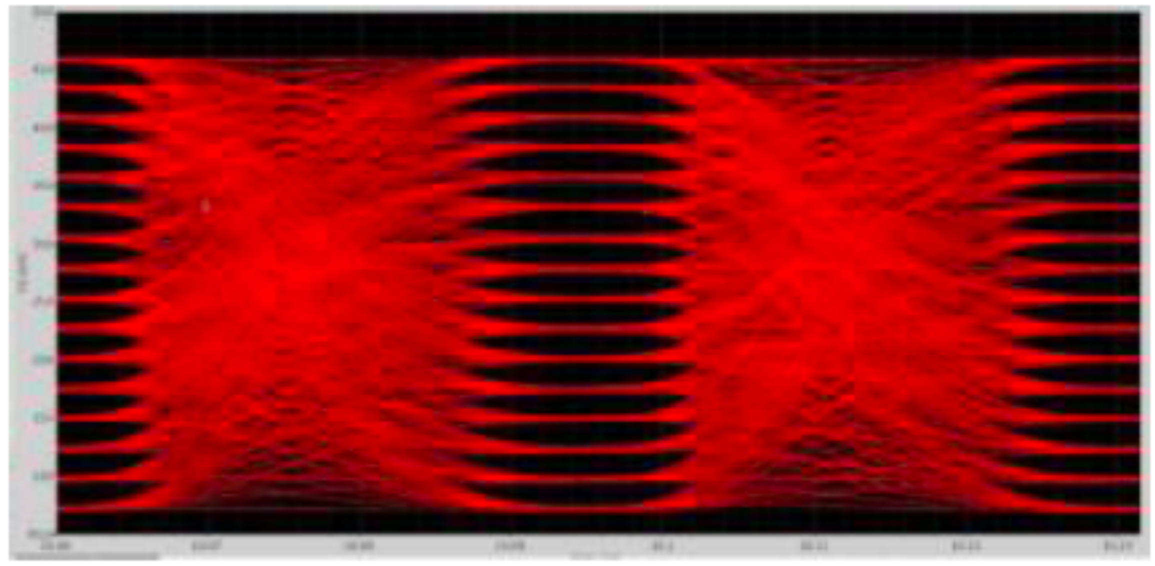
Optical transceiver scaling

Increasing data rates

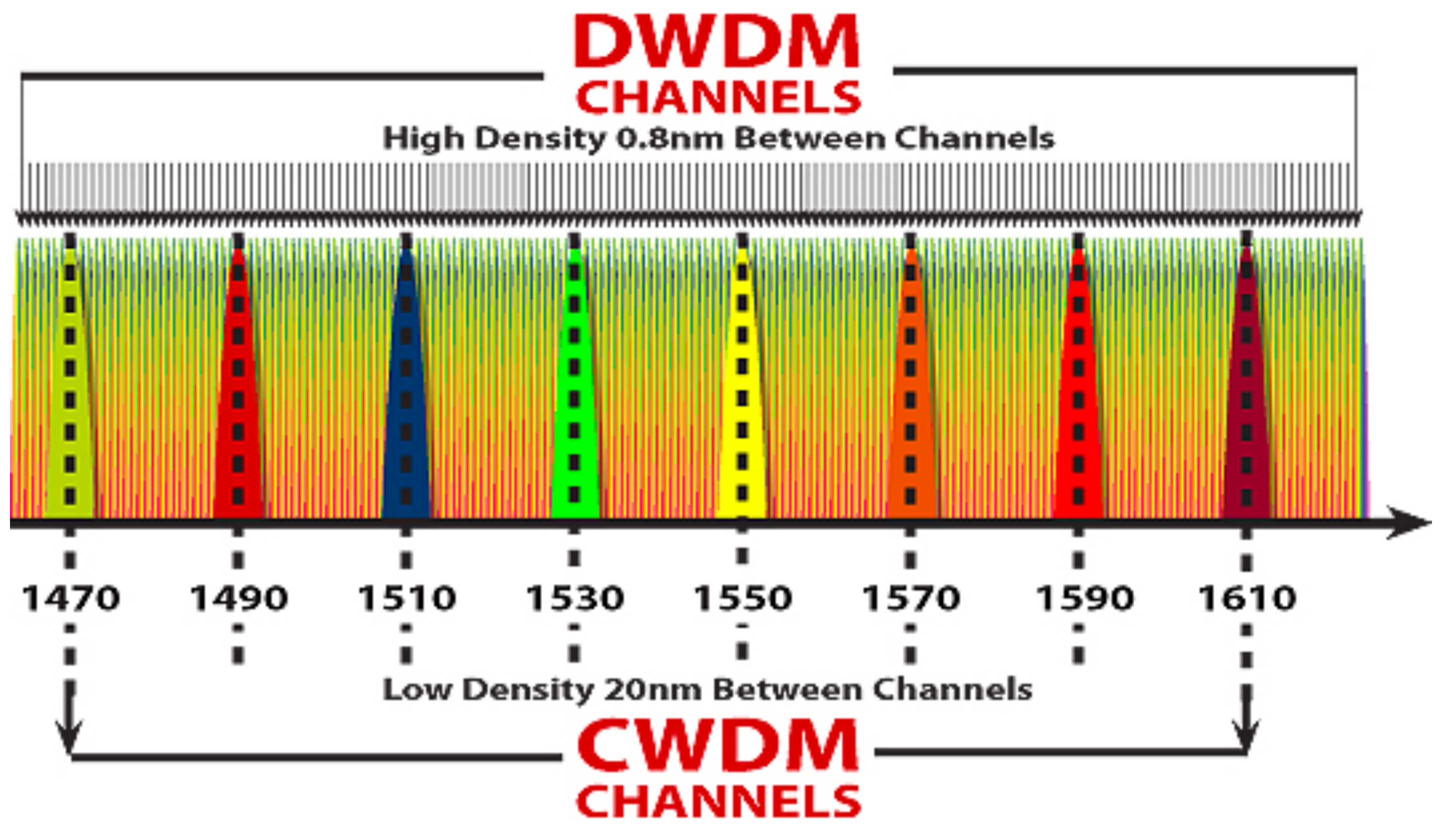
50 G
25 G
10 G
Faster channels

More bits/symbol
1 bit
2 bit
4 bit

1 λ   4 λ   8 λ
More channels



PAM-16 (LightWire/Luxtera)



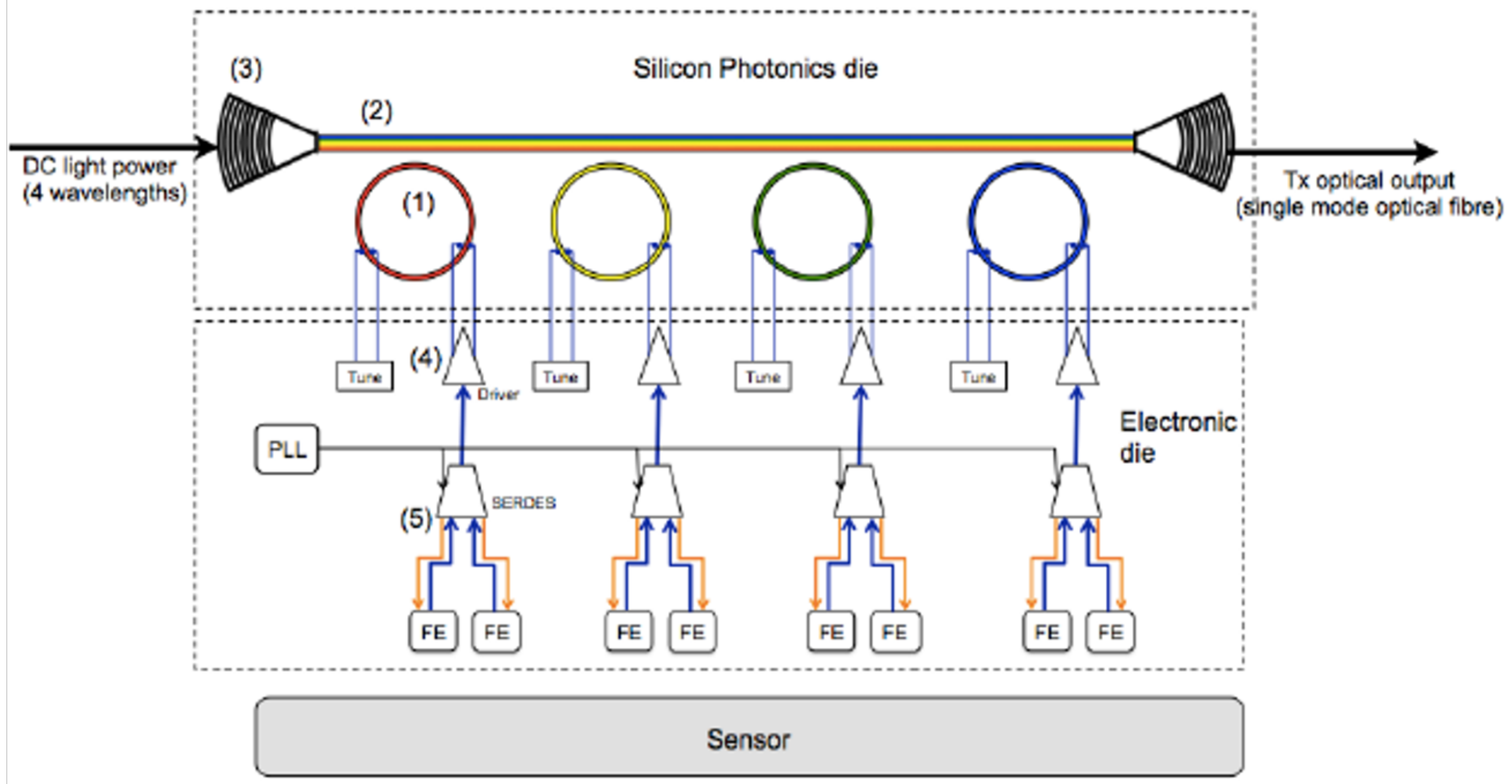
NRZ
PAM-4
QPSK
…

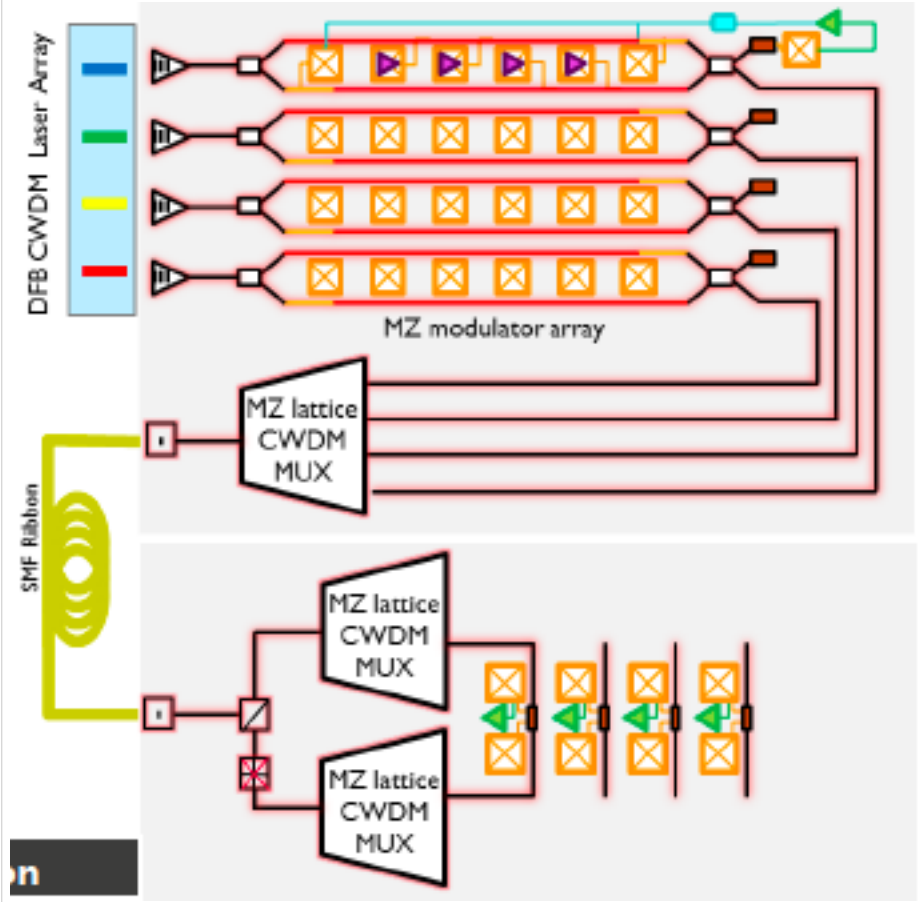
Wavelength Division Multiplexing (WDM)
Spatial Division Multiplexing (SDM)
Polarisation Division Multiplexing (PDM)
…

Silicon Photonics systems for HEP

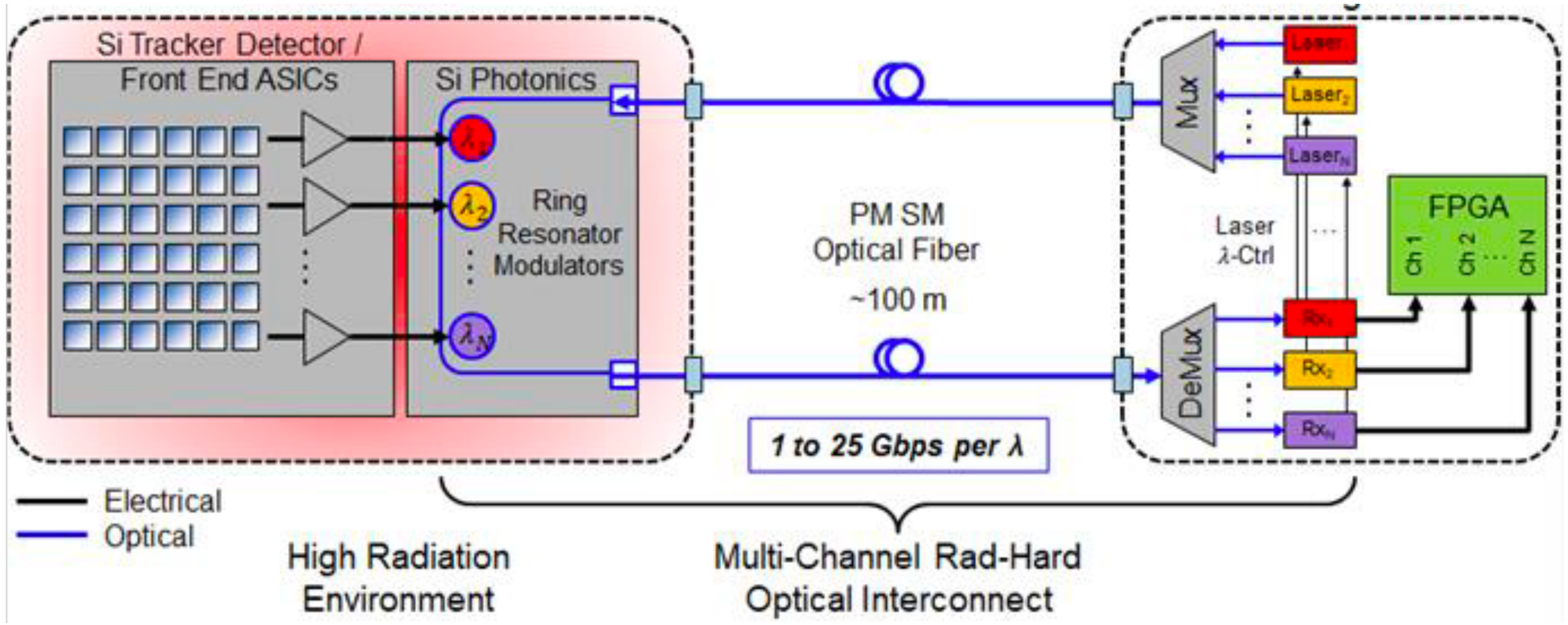
Possible architectures

- **High data rate: one fibre per Silicon Sensor (CERN, INFN, KIT)**
  - Use CWDM 4x25 Gb/s=100 Gb/s
  - Can use both MZM or RM
- **Many "low" rate over one fibre (LBNL, FNAL, UCSB & Freedom Photonics)**
  - Use DWDM
  - Separate RM from one or more detectors add different λ's on the same fibre





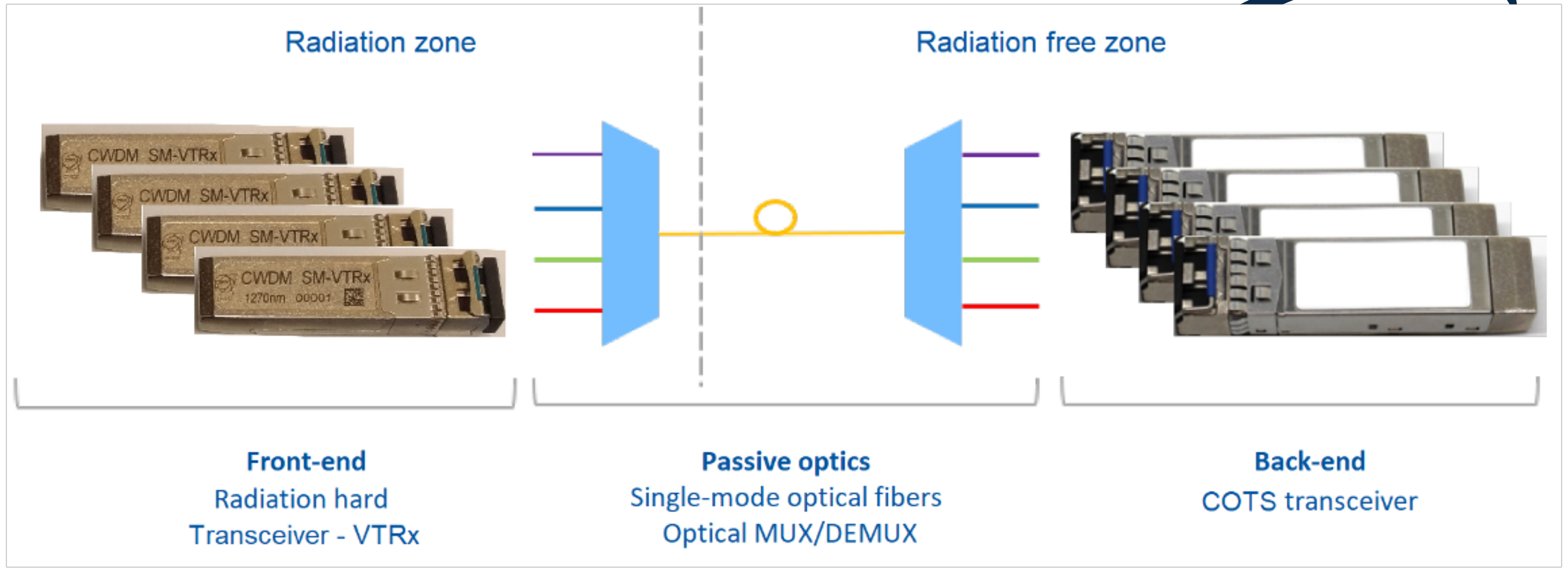
https://doi.org/10.1117/12.2615266

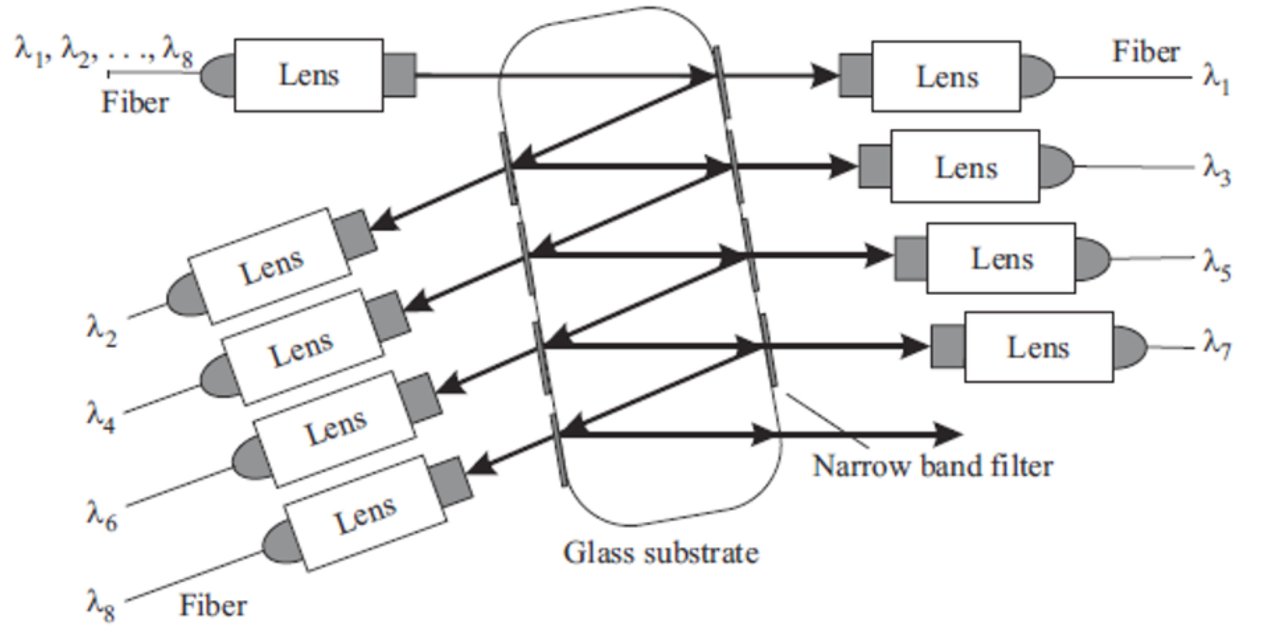


Silicon Photonics

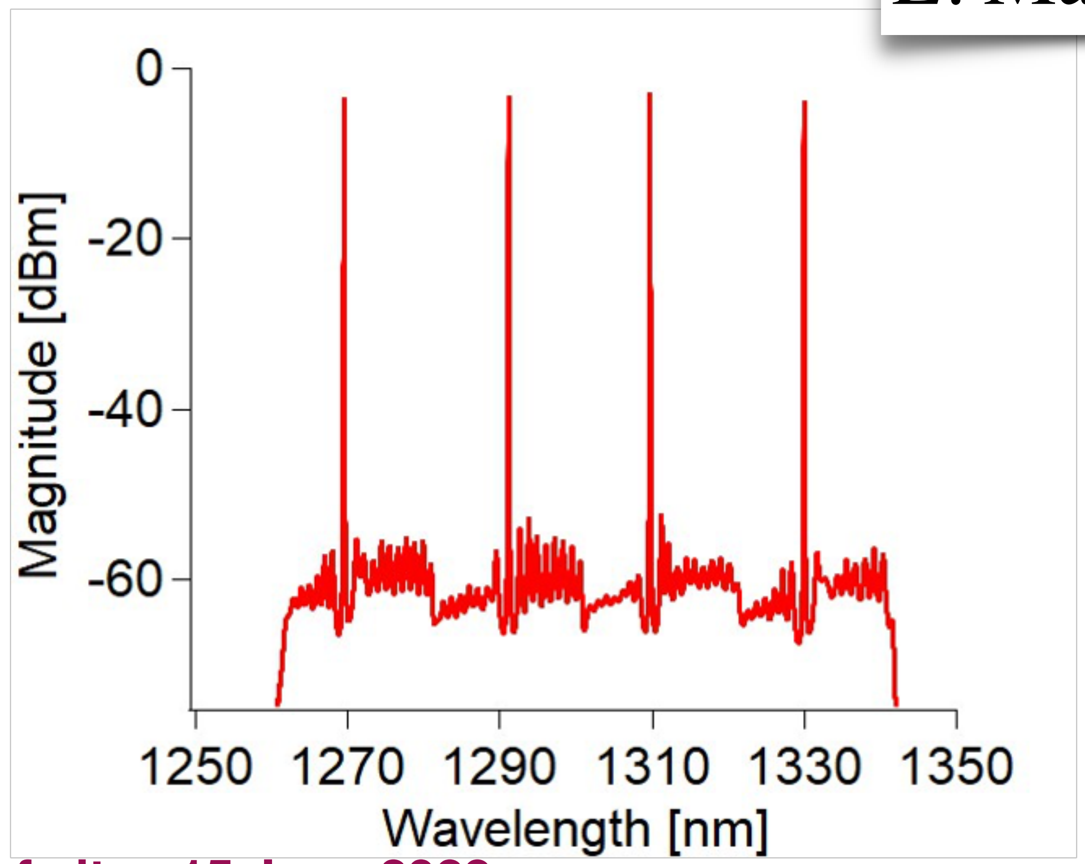
CWDM testing

- CWDM tested at O-band (1310 nm)
  - Nice to be repeated for C-band (1510 nm)
- Both laser sources and MUX have started to be tested for operations in the cavern
  - Neutrons ~few 10^{14} n/cm^2
  - Gamma ~11 kGy



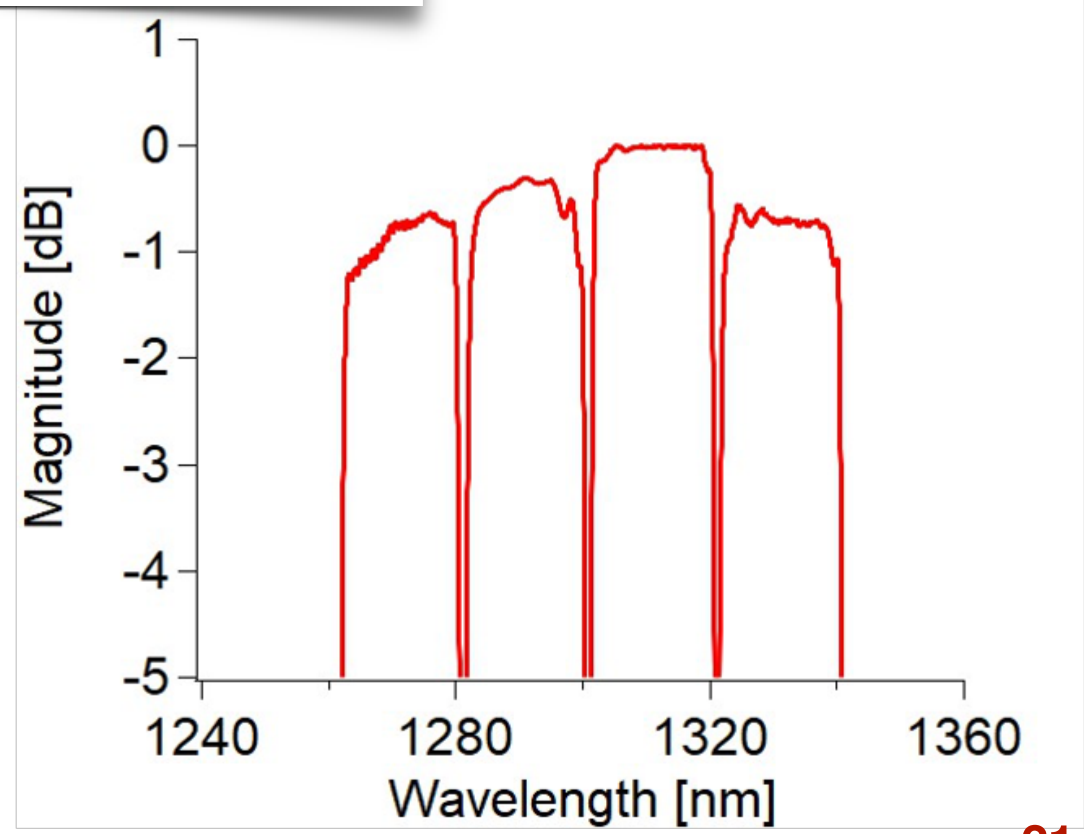


Optical spectrum @ channel output



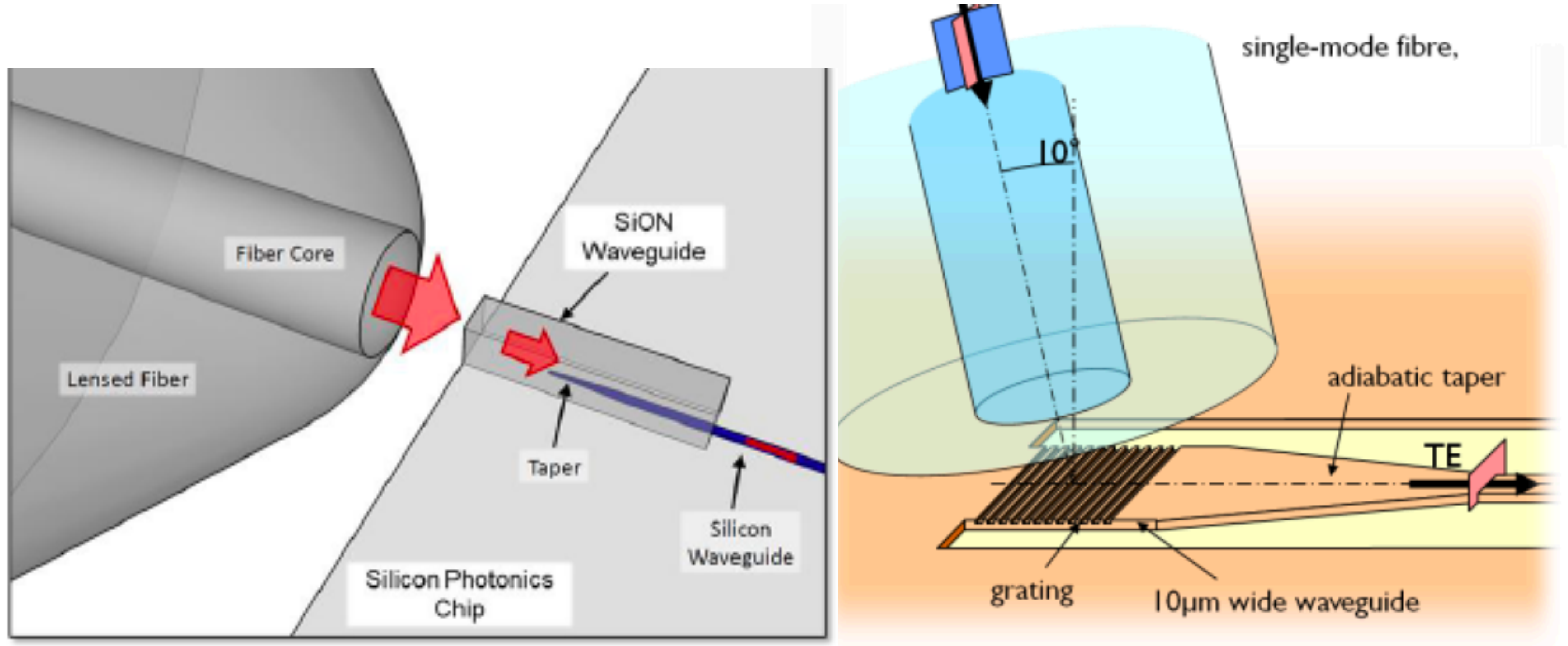
Optical spectrum of the CWDM MUX

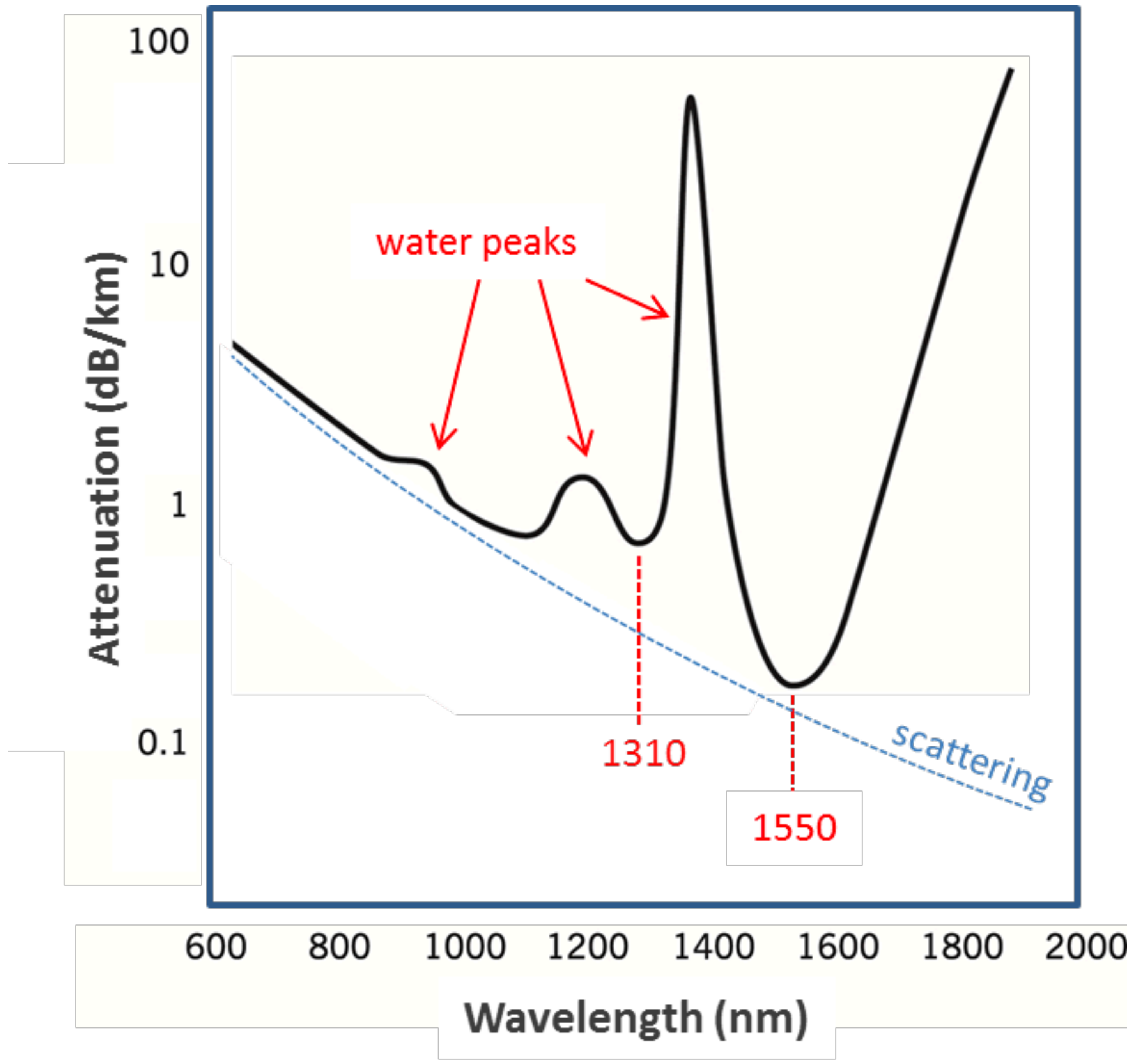
L. Marcon - TWEPP 2022



Silicon Photonics open issues

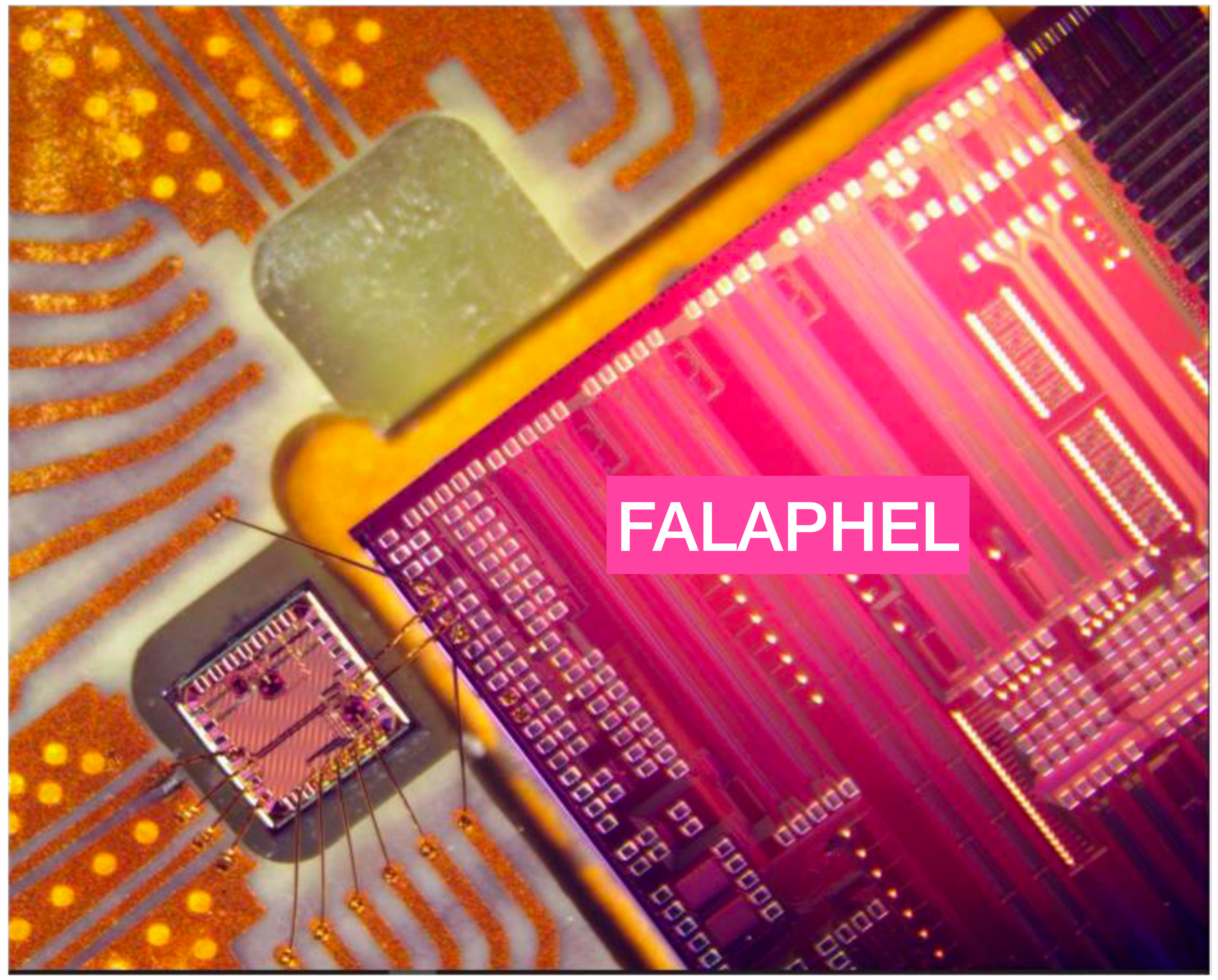
- **Modulator choice**
  - RM temperature sensitive wrt MZM but require lower driving voltages
- **Multiplexing scheme**
  - CWDM (few λ) vs DWDM (many λ)
  - Explore space division multiplexing (SDM) and polarisation division multiplexing (PDM)
  - Photonics switches needed
- **Fibre qualification and optical band**
  - Fibre characteristics (Chromatic Dispersion, Polarisation, Attenuation, radiation hardness, non-linear effects …)
  - Look at trends in data centres: O-band for 100G, C-band for 400ZR





Silicon Photonics open issues

- **Radiation tolerance**
  - *Process dependent SiPh chip (doping)*
    - Only few foundries tested so far, think of whom will be available at the time
  - Explore ultimate device limits in view of FCC-hh
    - Might be difficult to find irradiation sources (what's happening in nuclear fusion ?)
  - Explore radiation hardness of SiPh laser sources and fibres
- **Packaging**
  - Integration of driver and PIC: flip-chip/wire-bond/TSV/TGV
  - Laser integration on-chip for low-radiation applications?



General system aspects

- Backend boards use FPGAs
  - Links (and ASIC) should be made compatible with FPGA developments as much as possible
- Latency (introduced by FEC or protocols) must be considered especially for “real-time” applications (Triggers)
- Main limitations in data rate might not be the physical layer (opto-electronics could reach >40 Gb/s) but rather the ASIC (Serializers and drivers) and their radiation tolerance

Community competences

Silicon Photonics

- CERN - Established R&D program through EP-R&D WP6 and WP2 (2023-28)
  - PIC design (IMEC), RM and MZM and engineered radiation tolerance tests
  - Polarisation control, laser sources, optical MUX
  - System aspects (Modulation format, FEC, optical band, interface to COTS back end)
  - EIC development and integration studies
  - Targeting 4x CWDM
- INFN - (FALAPHEL, IGNITE) (2023-26)
  - PIC design (IMEC), RM, MZM, FMZM, EA, C-band
  - EIC development and integration studies
  - Targeting 4x CWDM

Community competences

Silicon Photonics

- KIT
  - PIC design (IMEC), RM, MZM
  - Photonics & ASIC packaging
  - Targeting 4x CWDM
- US (LBNL, FNAL, UCSB, Freedom Photonics)
  - PIC design (Global Foundries), Laser sources, radiation tolerance tests
  - Targeting DWDM with 1 fibre x N detectors

Collaborative issues

Resources and diversity

- Broad phase space requires to explore several solutions
  - Some “immediate” needs for HL-LHC (last phase) are currently being discussed
- New modulation schemes must be deployed for any kind of links
- Co-packaging (including sensors) needs close collaboration with ASIC developments
  - IGNITE @INFN will start investigating
- Rad-hard testing might become an issue
  - 250 MGy and 10^{17} n/cm^2 for FCC-hh

Conclusions

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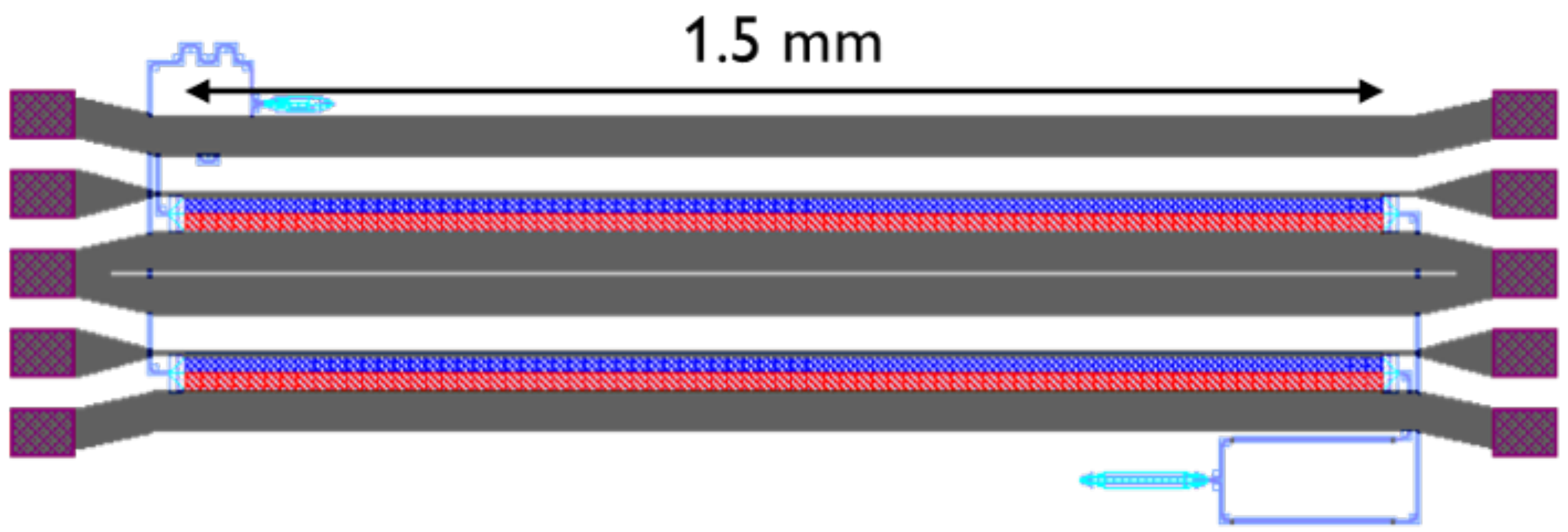
- Silicon photonics will likely become the standard for future High-Energy high-speed links
  - It is sufficiently radiation tolerant with some process modifications
  - It could offer reaching at least 100 Gb/s bandwidth links with coarse WDM modulation techniques
    - Even further speeds could be reached by increasing suitable electronic circuits (maybe beyond 28 nm), adopting other modulation schemes (such as PAM4) or using more wavelengths
  - Vigorous R&D in progress but need to explore many corners and more groups and synergies sought

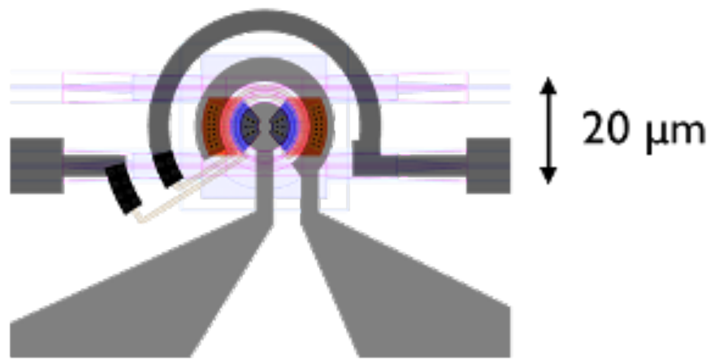
Thank you for your attention

BACKUP

Comparison

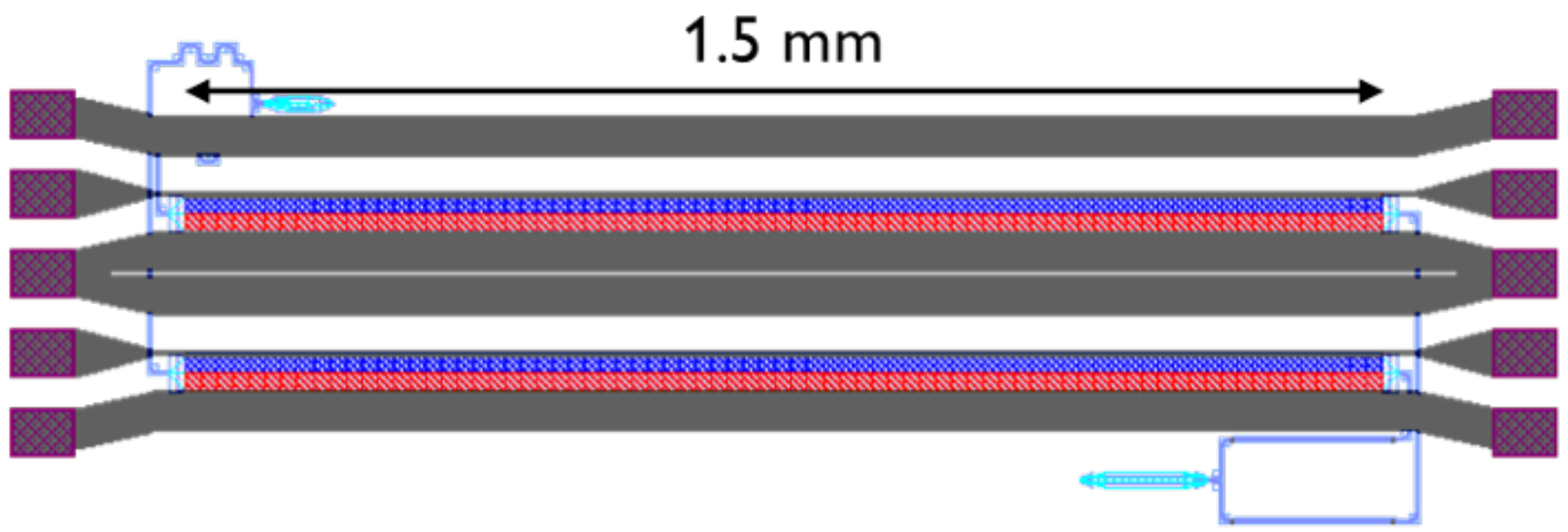
Metrics	Interferometer-based	Resonator-based
Optical bandwidth	Broadband	Narrow-band (< 1 nm)
Process/Temperature sensitivity	Robust	Active resonance control required
Footprint	Large (mm-scale)	Small (10 μm-scale)
Power consumption	Large (DC bias + RF)	Small (tiny capacitive load)
Common driving condition	Traveling-wave (RF terminated)	Lumped-element

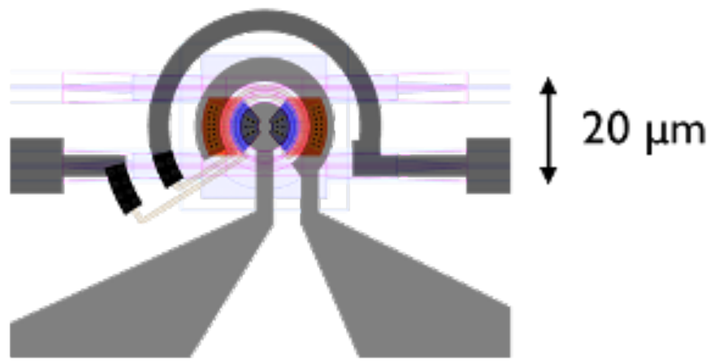




Comparison

Metrics	Interferometer-based	Resonator-based
Optical bandwidth	Broadband	Narrow-band (< 1 nm)
Process/Temperature sensitivity	Robust	Active resonance control required
Footprint	**100 μm**	Small (10 μm-scale)
Power consumption	**Only RF**	Small (tiny capacitive load)
Common driving condition	**Lumped-element**	Lumped-element





Lumped element MZM

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- Electrodes size should be well below RF wavelength to have the same voltage on the entire phase shifter length
- Non-terminated device: no DC power consumption and on-chip thermal dissipation
- Bandwidth limits:
  - Electrical RC-limit
  - Optical transit time

$$f_{3\mathrm{dB,ele}} \approx \frac{1}{2\pi Z_S C_{\mathrm{pn}}}$$

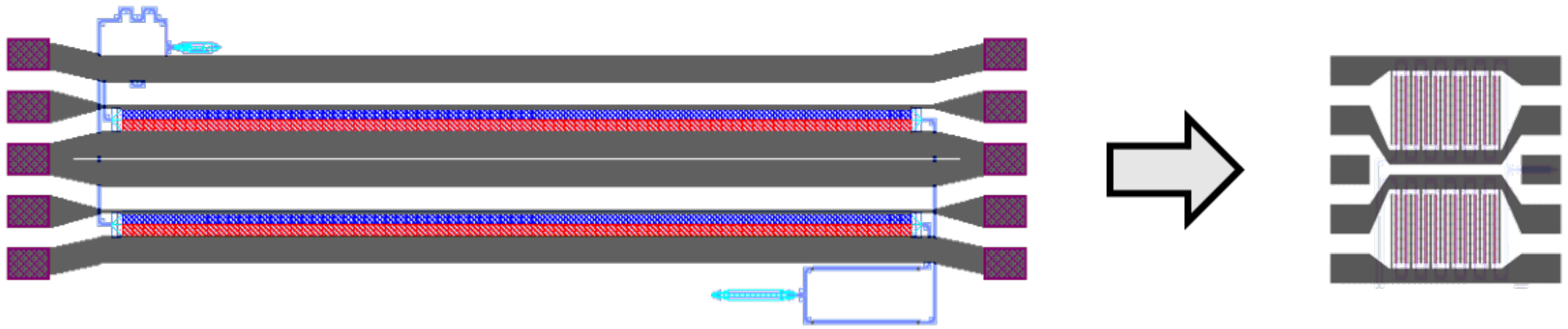
PN junction capacitance

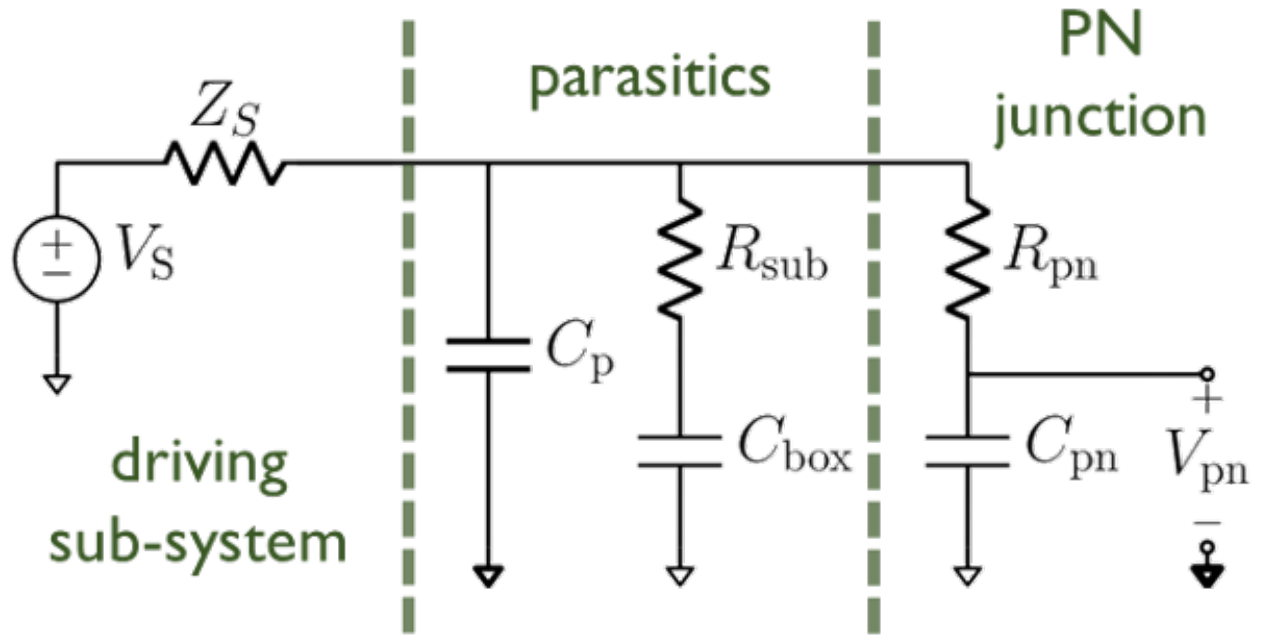
driving impedance

$$f_{3\mathrm{dB,opt}} \approx \frac{0.44 \cdot c}{n_g L}$$

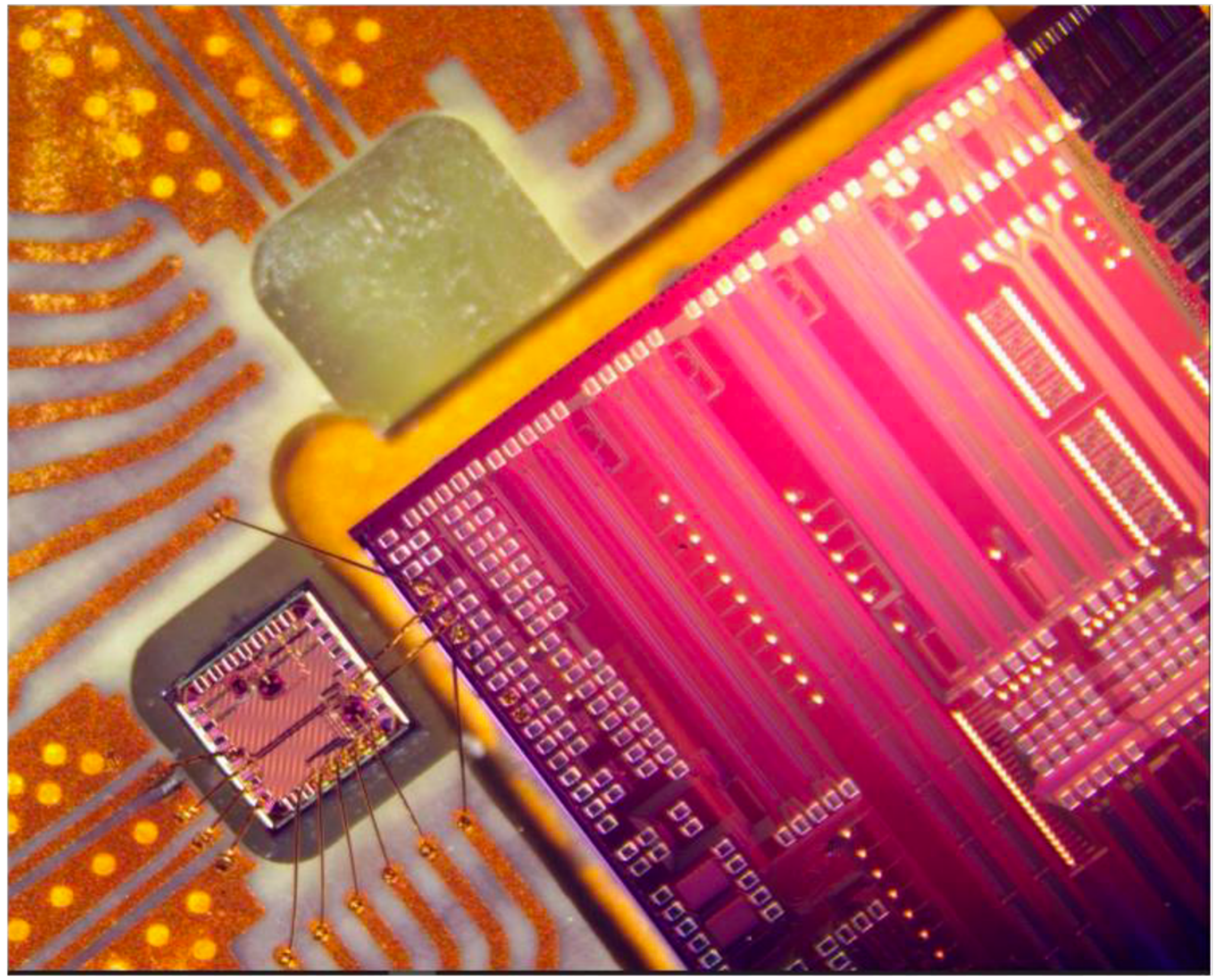
group index

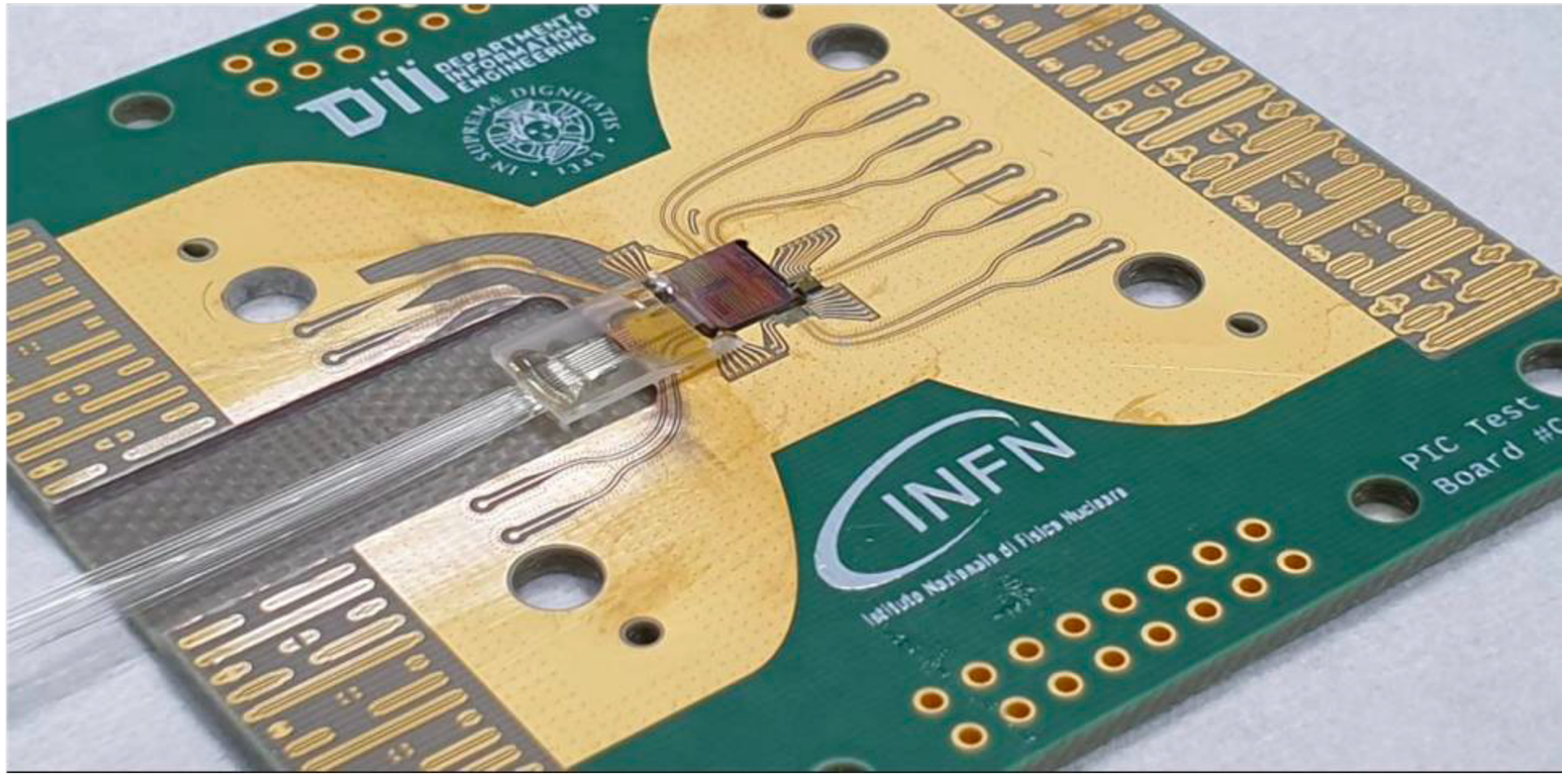
optical length





EIC-PIC integration





28 nm HPC Building blocks submission (28/10/2020)

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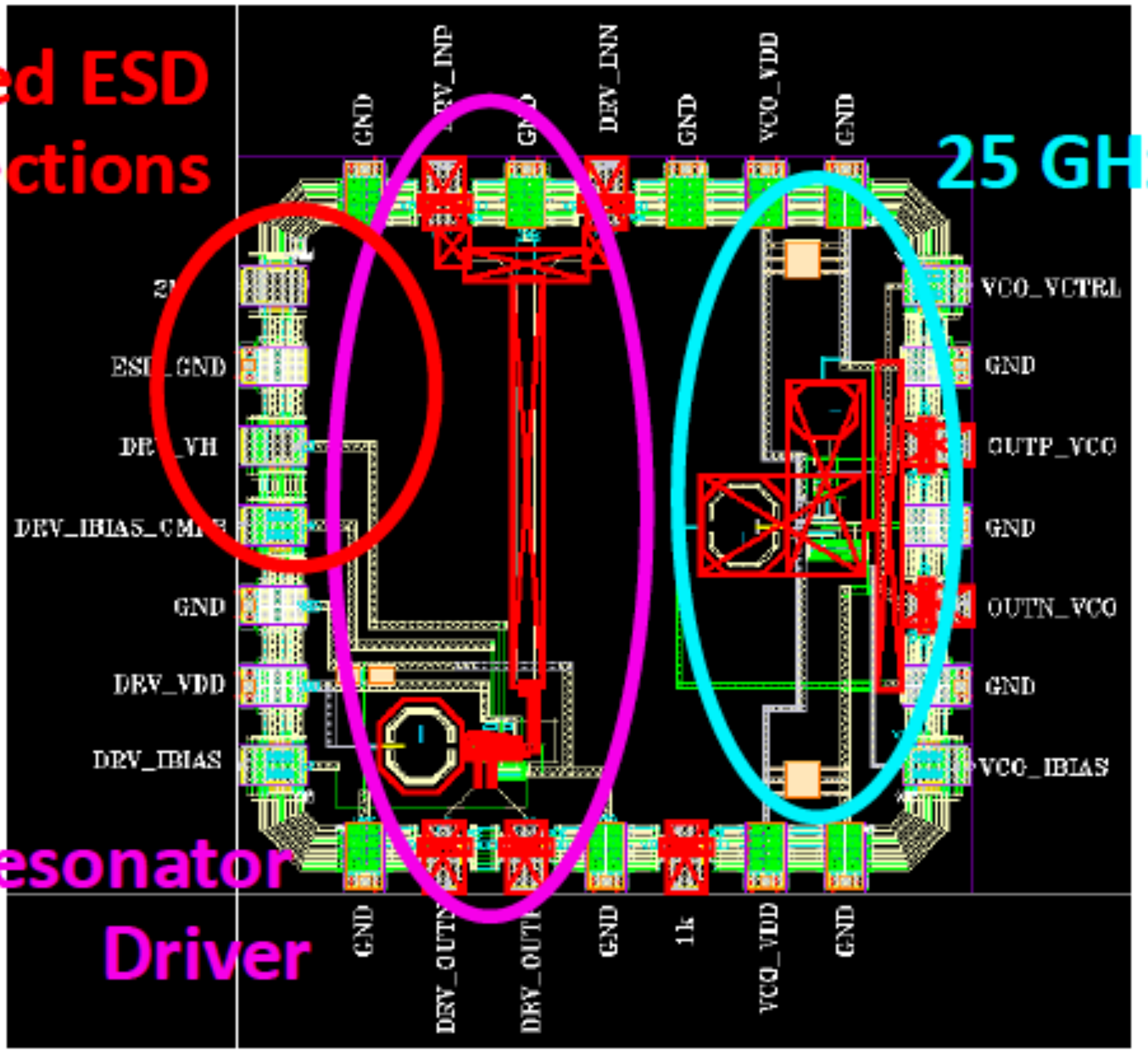


1 mm x 1 mm µblock
in 28 nm HPC

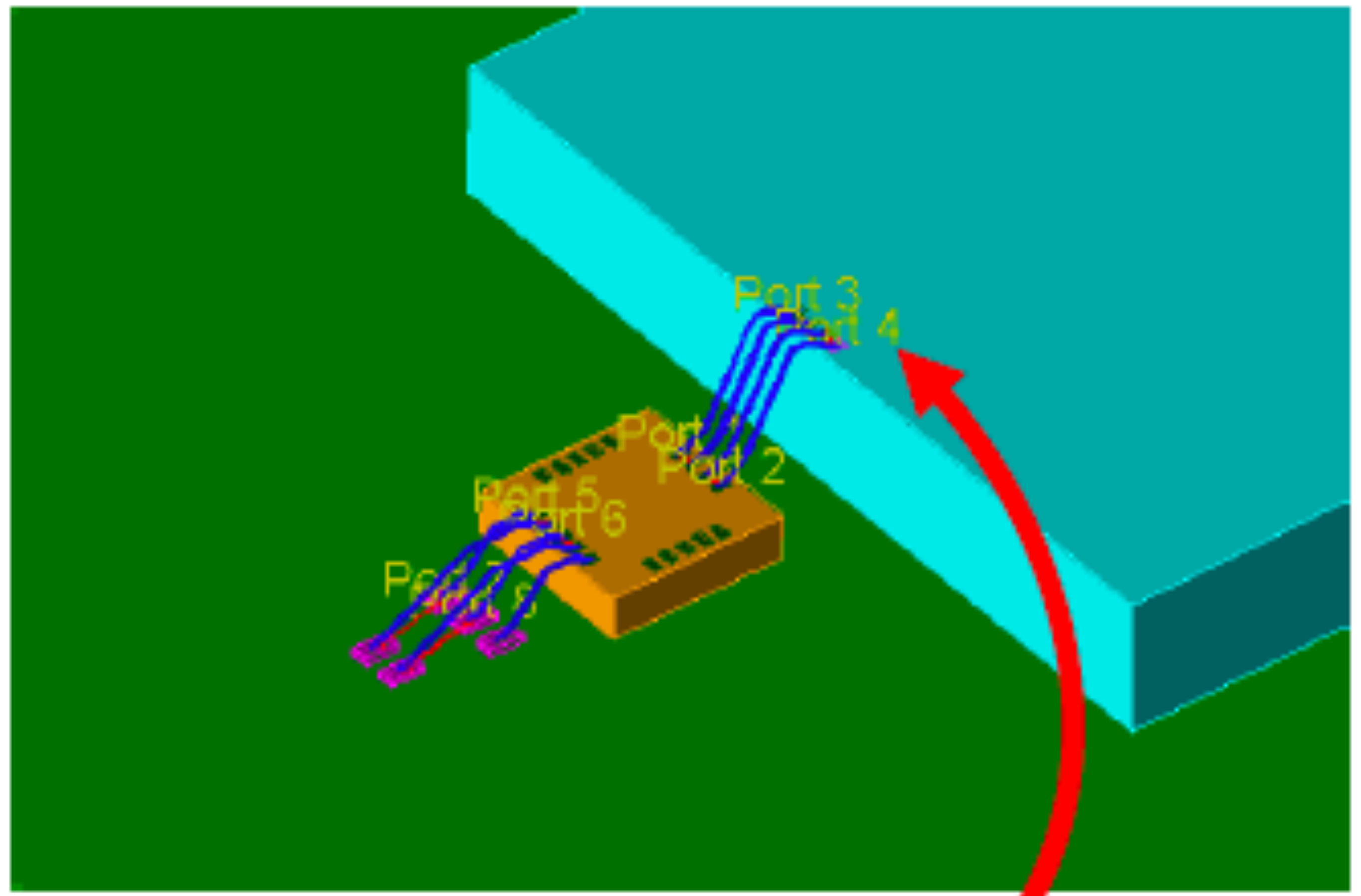
PAD limited chip

Falaphel

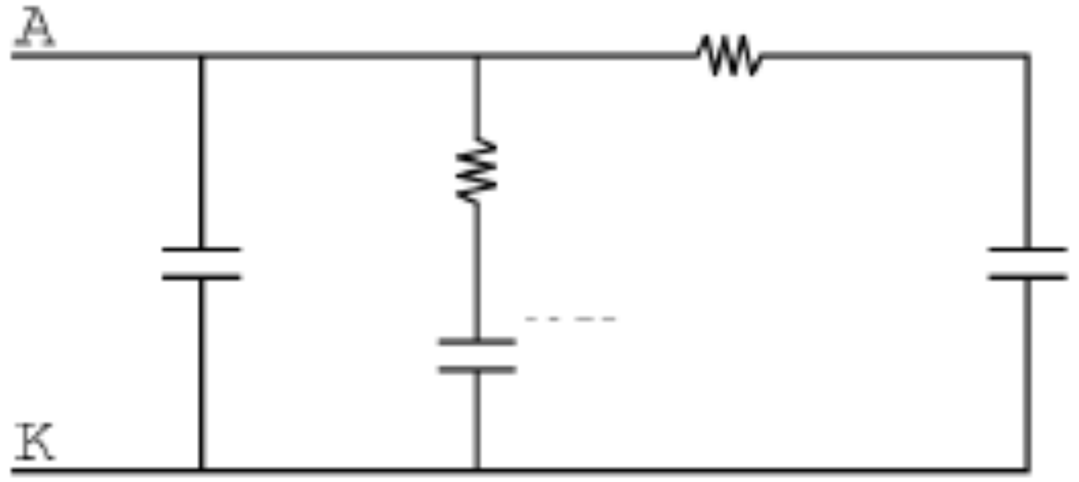
25 Gb/s Ring Resonator Driver in 28 nm (Backend)

INFN
Istituto Nazionale di Fisica Nucleare

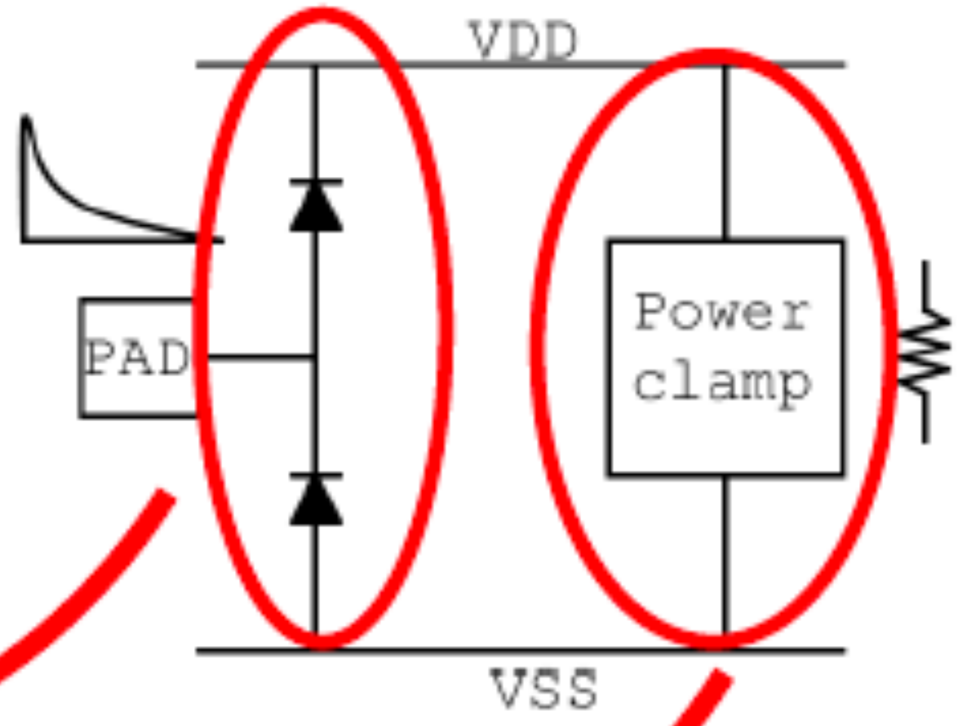
In-output modelling



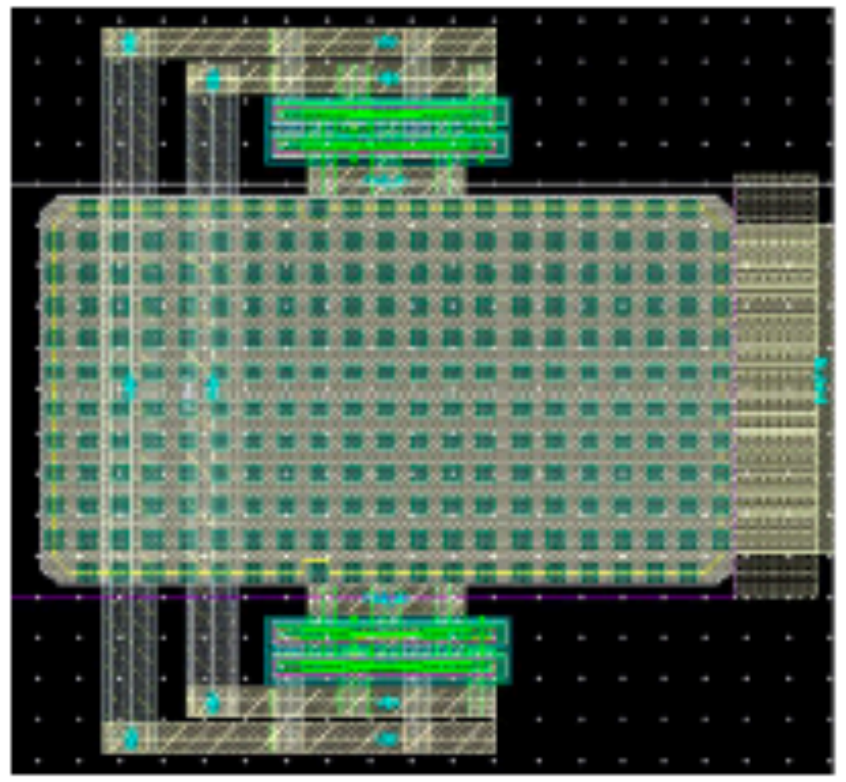
Electro-optical modulator model



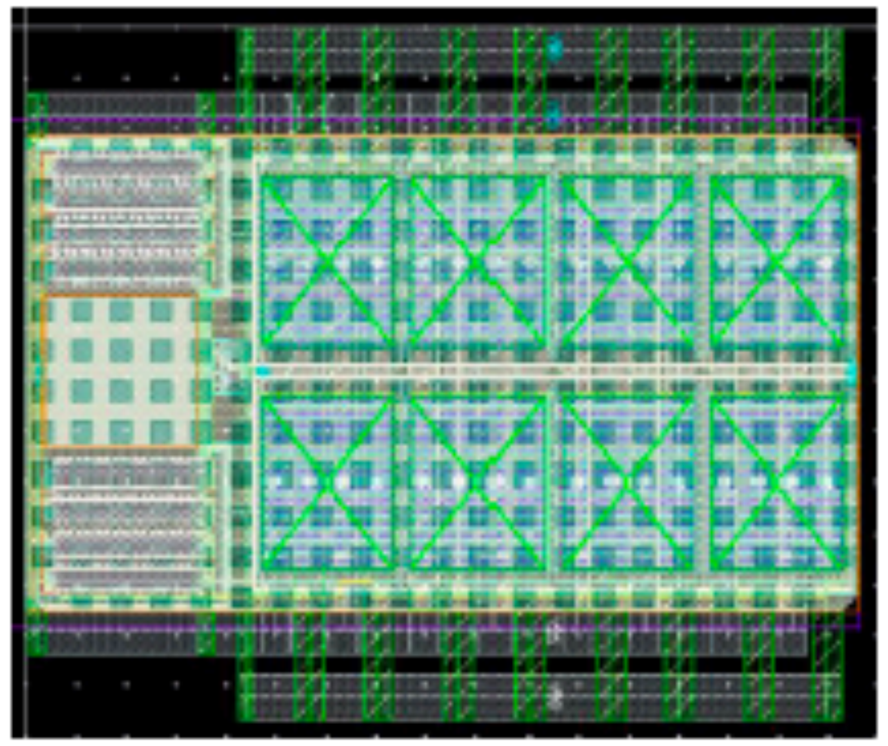
RF PAD & ESD design



1 kV & 2 kV HBM ESD
Low capacitance

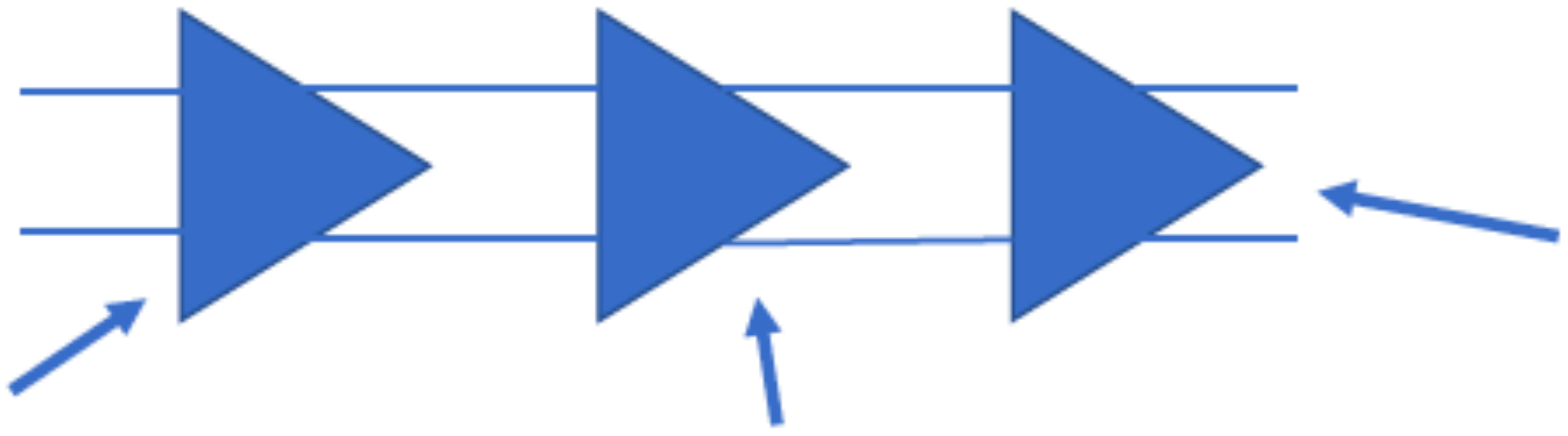


Low impedance power clamp

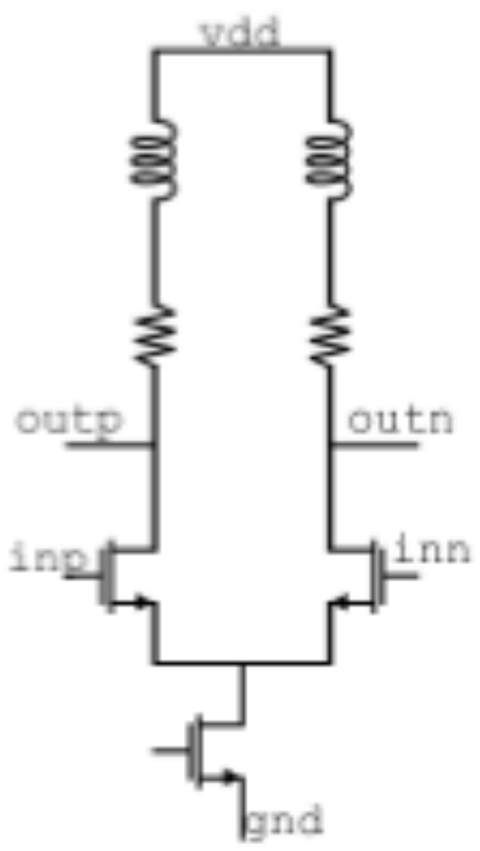


Falaphel

25 Gb/s Ring Resonator Driver in 28 nm



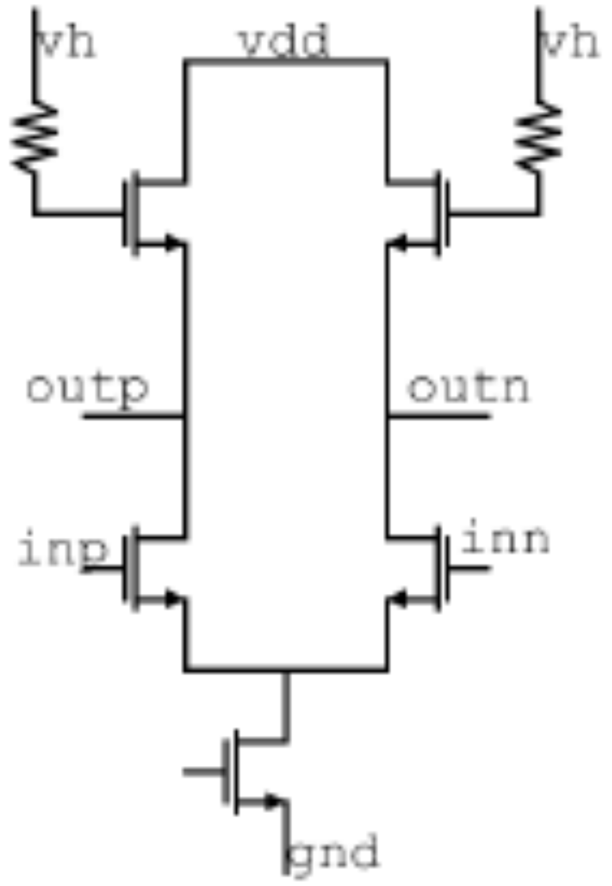
Output stage:
-50 Ω output resistance
-±500mV amplitude
-Passive bandwidth enhancement



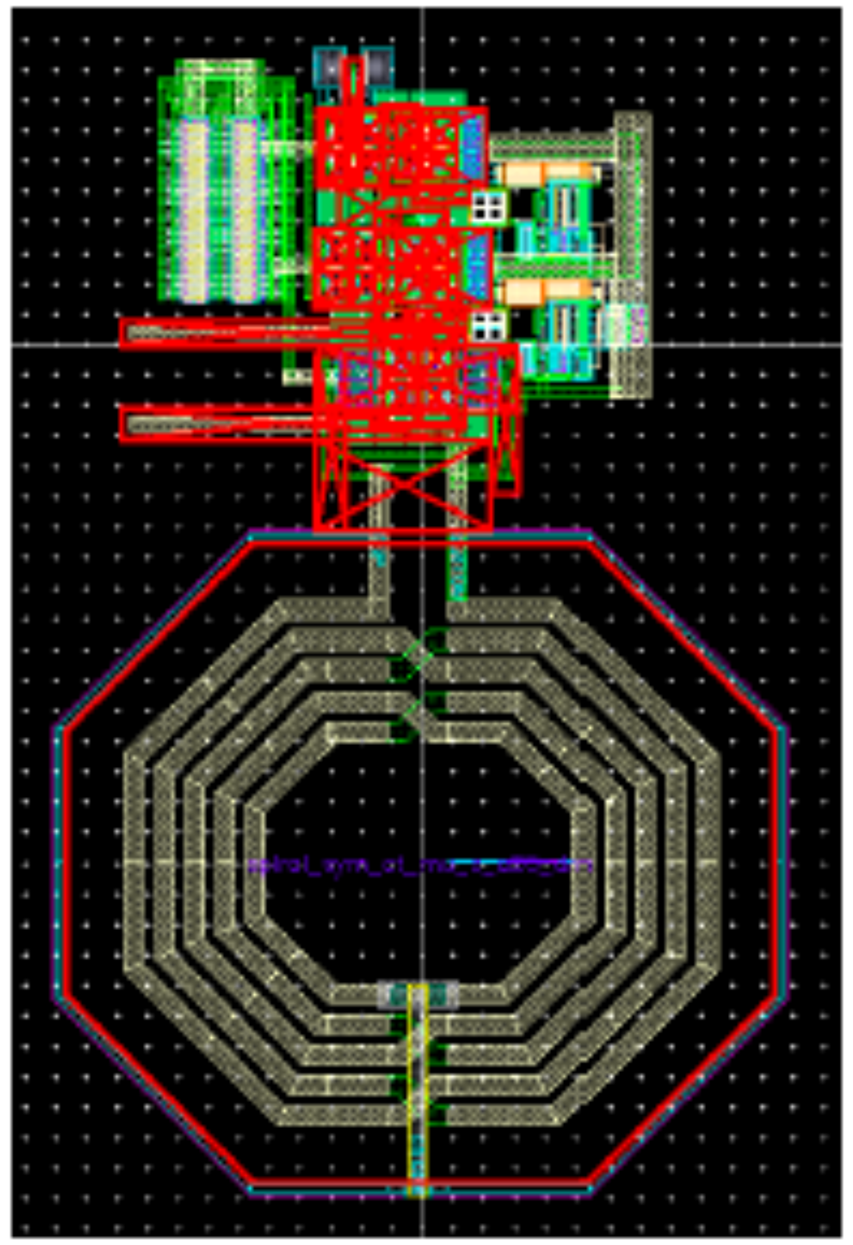
Falaphel

Receiver:
-Active bandwidth enhancement
-Common mode correction

Predriver:
-Active bandwidth enhancement
-Common mode correction



Layout area: 200 x 120 μm²
Consumption power: 23.85 mW



System simulation with post-layout blocks