ASPICs for High Energy Physics Applications

Deepak Gajanana, Martin van Beuzekom
Nikhef (National Institute for Subatomic Physics), Amsterdam
Xaveer Leijtens
Eindhoven University of Technology, Eindhoven

TIPP '14 International Conference on Technology and Instrumentation in Particle Physics
2 – 6 June 2014 / Amsterdam, The Netherlands

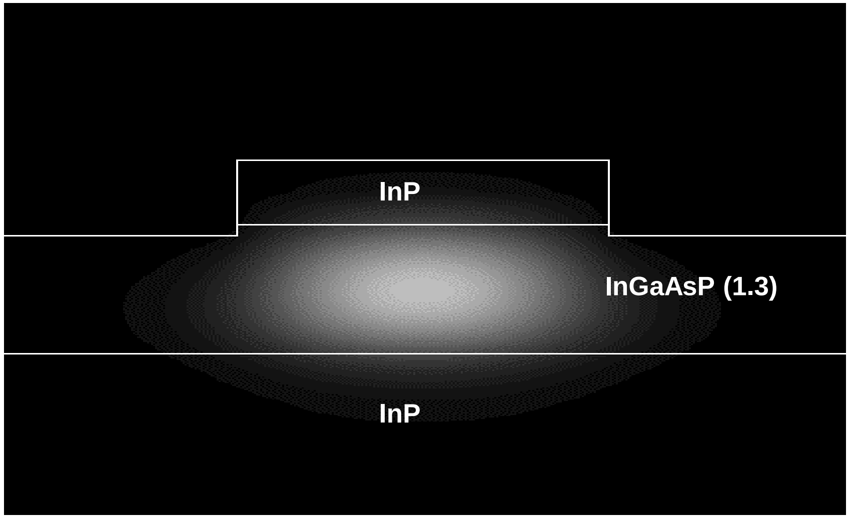
"Instrumentation as enabler of Science"

Contents

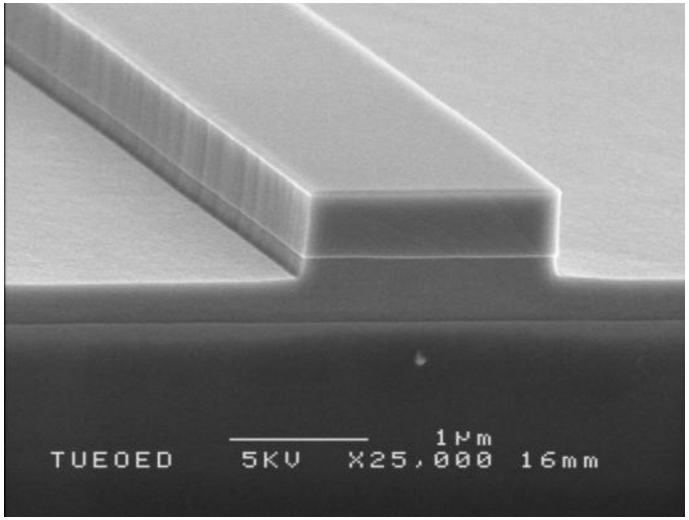
1. Introduction
2. Generic Integration Technology (InP)
   - Example photonic ICs
   - Application in HEP experiments

"An Application Specific Photonic Integrated Circuit integrates multiple optical components like sources, detectors, modulators etc. to save area, cost, power and add more functionality."

Optical Waveguide



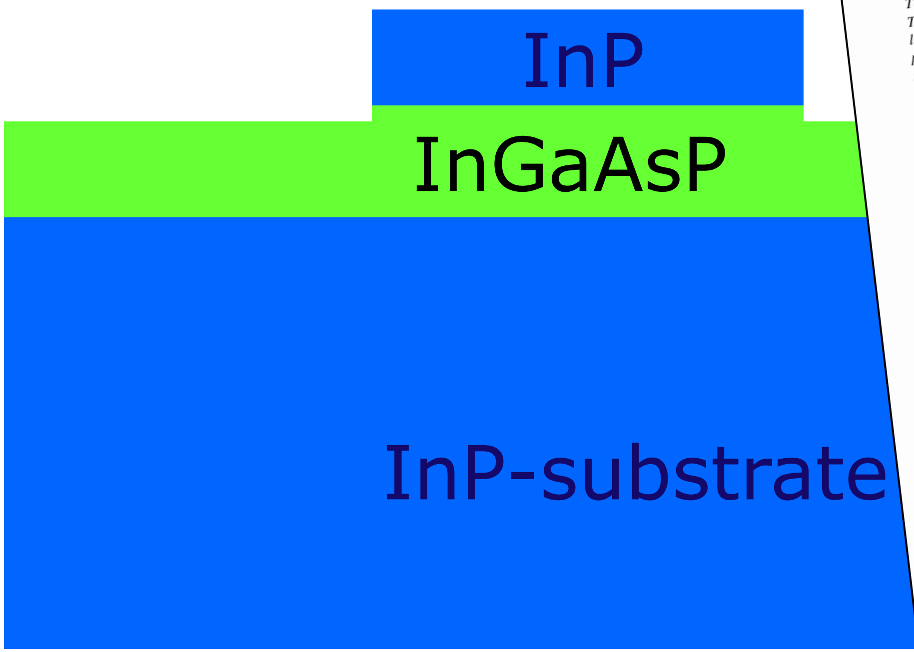
Simulated mode distribution

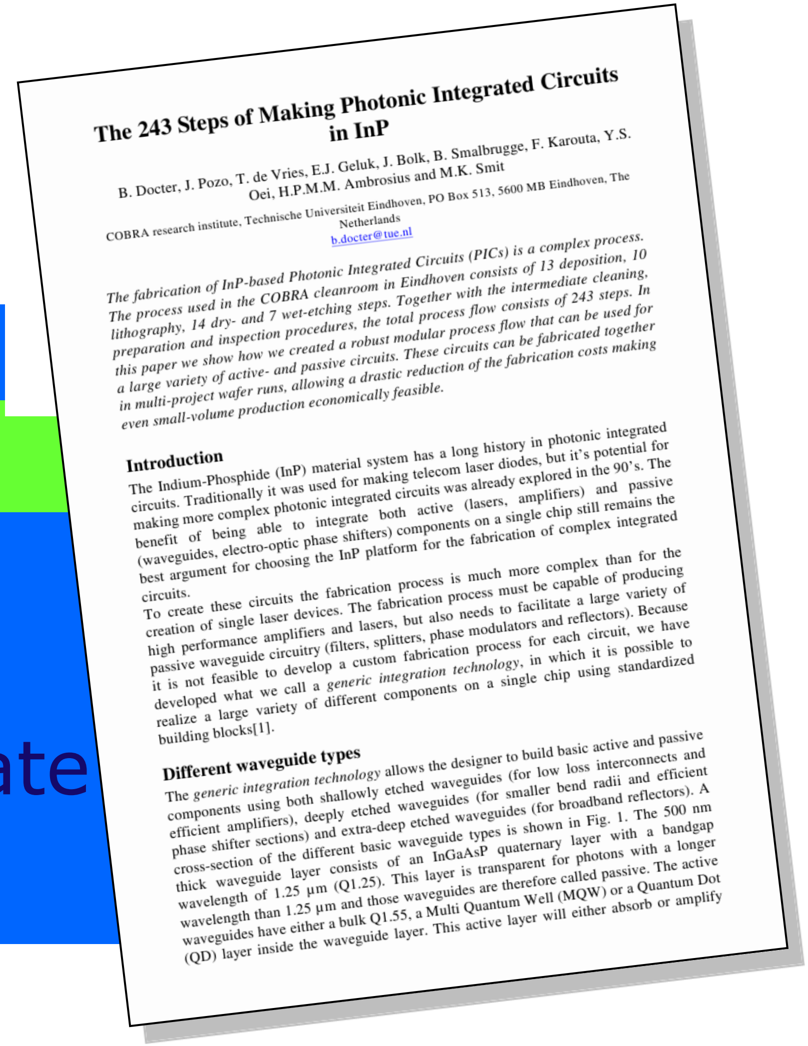


Scanning Electron Microscope (SEM) photograph

Materials could be Si, Binary, Ternary and Quaternary semiconductors.
Indium Phosphide (InP) in combination with InGaAsP has advantages of making light sources, detectors and other circuits at 1550 nm (3rd generation telecom wavelength).

Waveguide fabrication process





The 243 Steps of Making Photonic Integrated Circuits in InP

B. Docter, J. Pozo, T. de Vries, E.J. Geluk, J. Bolk, B. Smalbrugge, F. Karouta, Y.S. Oei, H.P.M.M. Ambrosius and M.K. Smit

COBRA research institute, Technische Universiteit Eindhoven, PO Box 513, 5600 MB Eindhoven, The Netherlands
b.docter@tue.nl

The fabrication of InP-based Photonic Integrated Circuits (PICs) is a complex process. The process used in the COBRA cleanroom in Eindhoven consists of 13 deposition, 10 lithography, 14 dry- and 7 wet-etching steps. Together with the intermediate cleaning, preparation and inspection procedures, the total process flow consists of 243 steps. In this paper we show how we created a robust modular process flow that can be used for a large variety of active- and passive circuits. These circuits can be fabricated together in multi-project wafer runs, allowing a drastic reduction of the fabrication costs making even small-volume production economically feasible.

Introduction

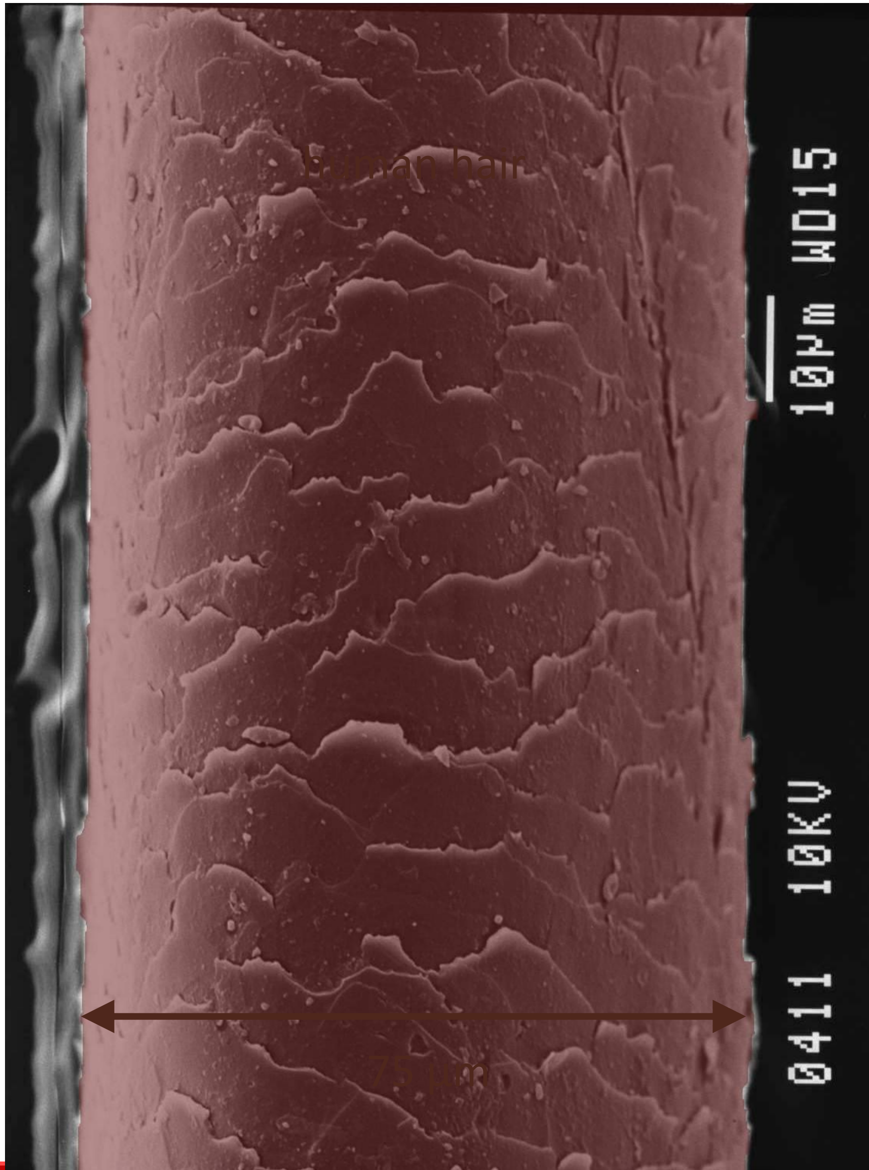
The Indium-Phosphide (InP) material system has a long history in photonic integrated circuits. Traditionally it was used for making telecom laser diodes, but it's potential for making more complex photonic integrated circuits was already explored in the 90's. The benefit of being able to integrate both active (lasers, amplifiers) and passive (waveguides, electro-optic phase shifters) components on a single chip still remains the best argument for choosing the InP platform for the fabrication of complex integrated circuits.

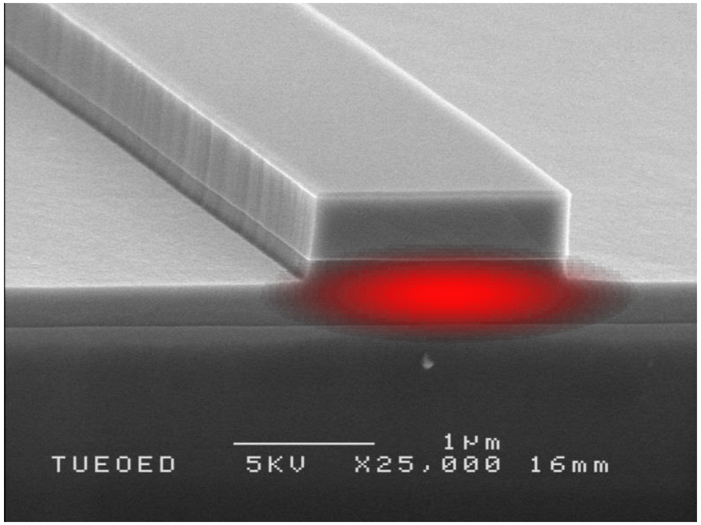
To create these circuits the fabrication process is much more complex than for the creation of single laser devices. The fabrication process must be capable of producing high performance amplifiers and lasers, but also needs to facilitate a large variety of passive waveguide circuitry (filters, splitters, phase modulators and reflectors). Because it is not feasible to develop a custom fabrication process for each circuit, we have developed what we call a *generic integration technology*, in which it is possible to realize a large variety of different components on a single chip using standardized building blocks[1].

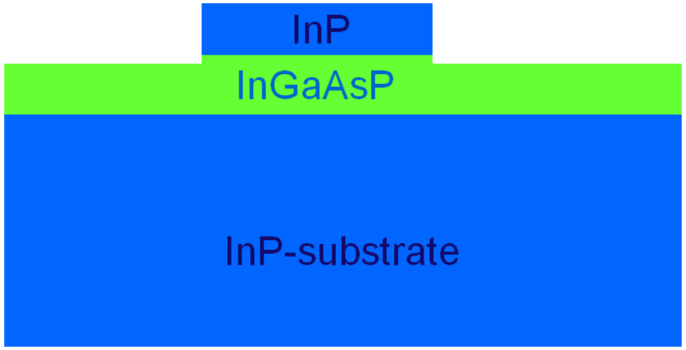
Different waveguide types

The *generic integration technology* allows the designer to build basic active and passive components using both shallowly etched waveguides (for low loss interconnects and efficient amplifiers), deeply etched waveguides (for smaller bend radii and efficient phase shifter sections) and extra-deep etched waveguides (for broadband reflectors). A cross-section of the different basic waveguide types is shown in Fig. 1. The 500 nm thick waveguide layer consists of an InGaAsP quaternary layer with a bandgap wavelength of 1.25 μm (Q1.25). This layer is transparent for photons with a longer wavelength than 1.25 μm and those waveguides are therefore called passive. The active waveguides have either a bulk Q1.55, a Multi Quantum Well (MQW) or a Quantum Dot (QD) layer inside the waveguide layer. This active layer will either absorb or amplify

Optical Waveguide

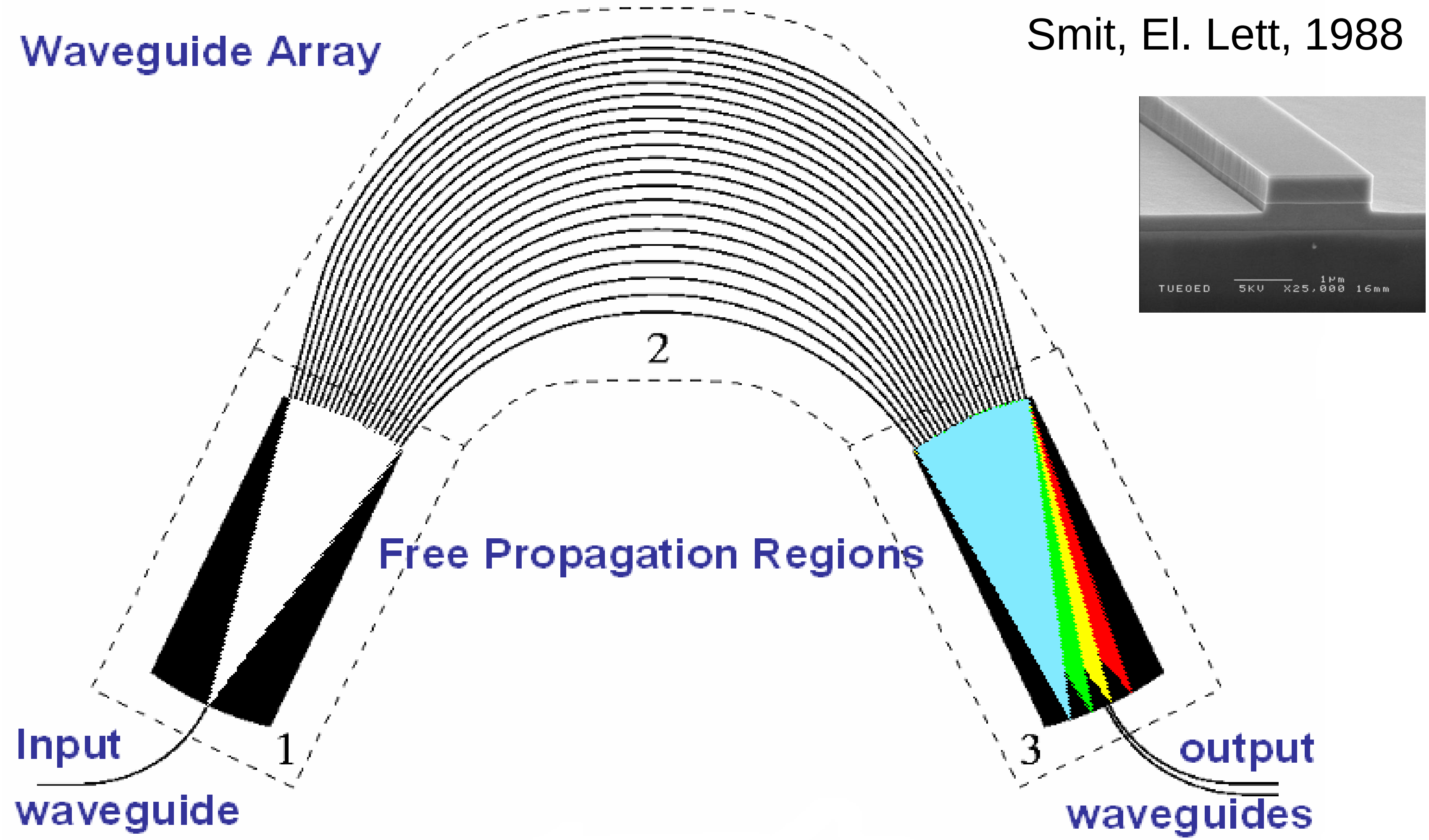




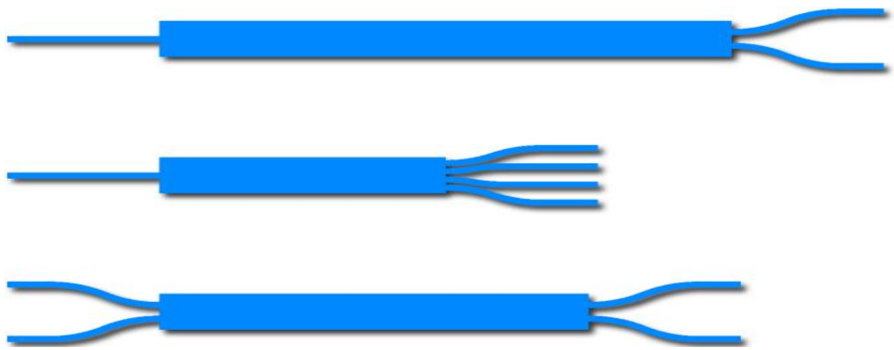


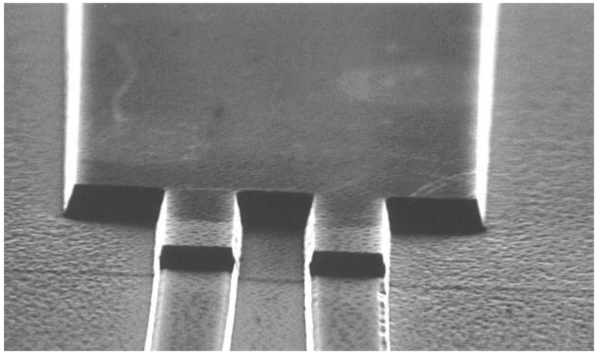
Arrayed Waveguide Grating (AWG) COBRA 1988

Smit, El. Lett, 1988

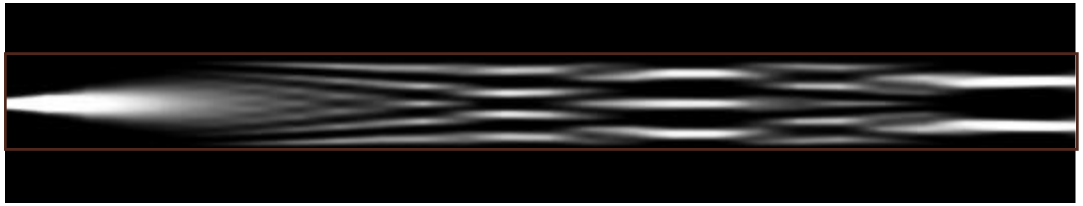


MMI (Multi Mode Interference) Couplers

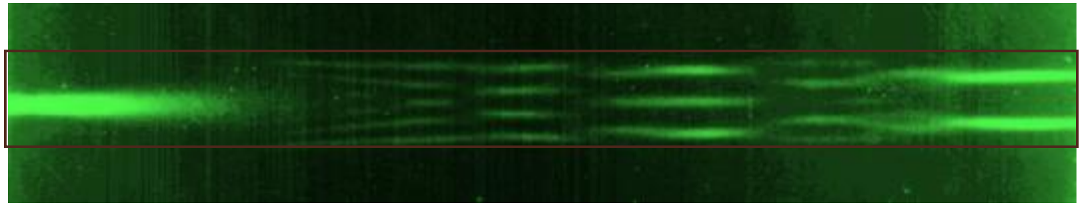




Geometry of MMI-couplers



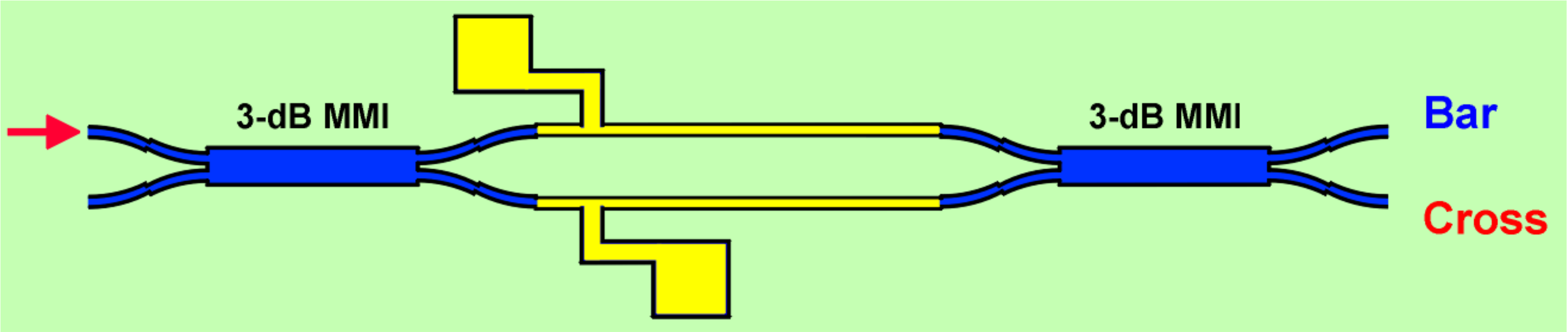
Simulated pattern

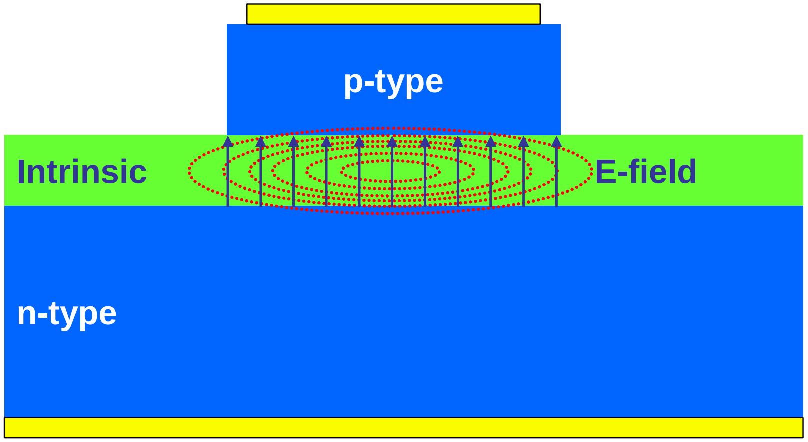


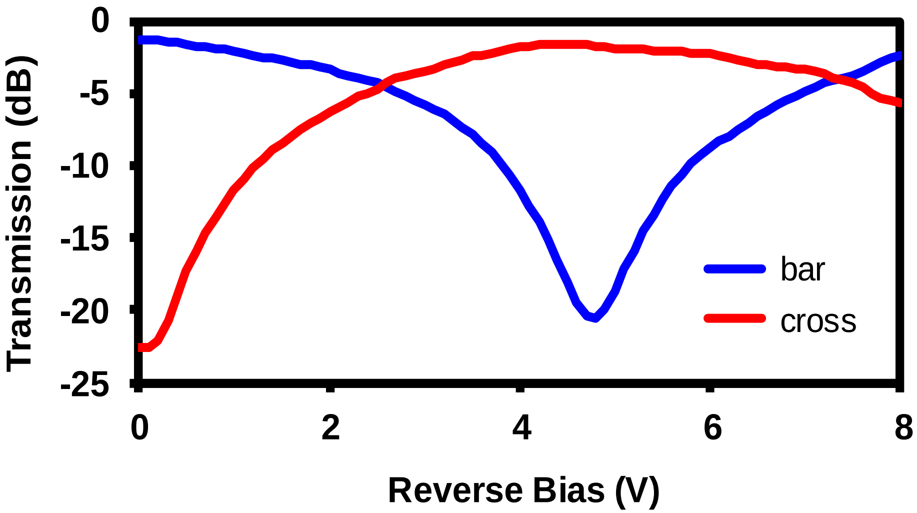
Experimentally imaged pattern

Acts as power splitter/combiner.
Various power ratios possible.

Mach Zehnder Switch

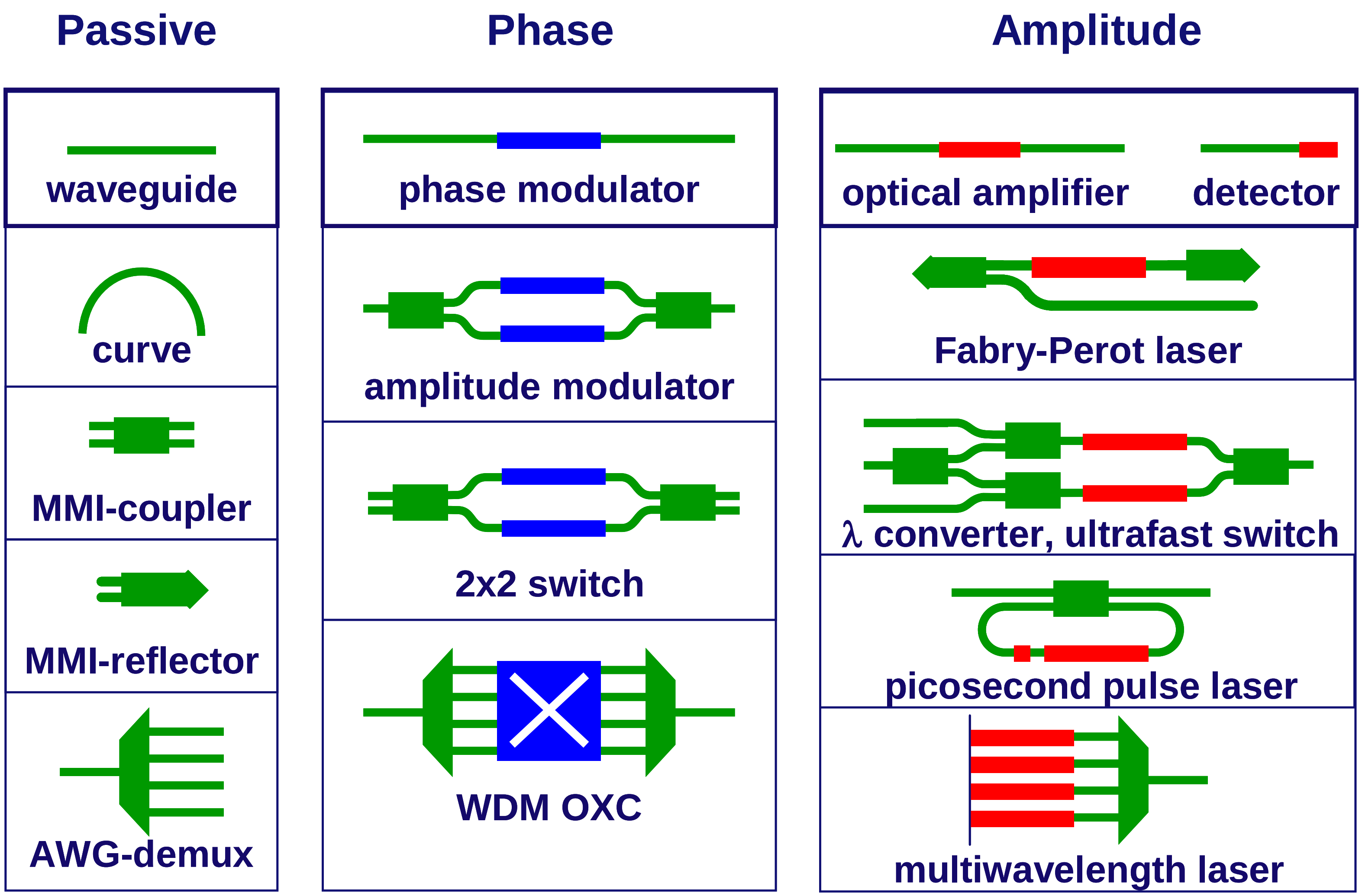




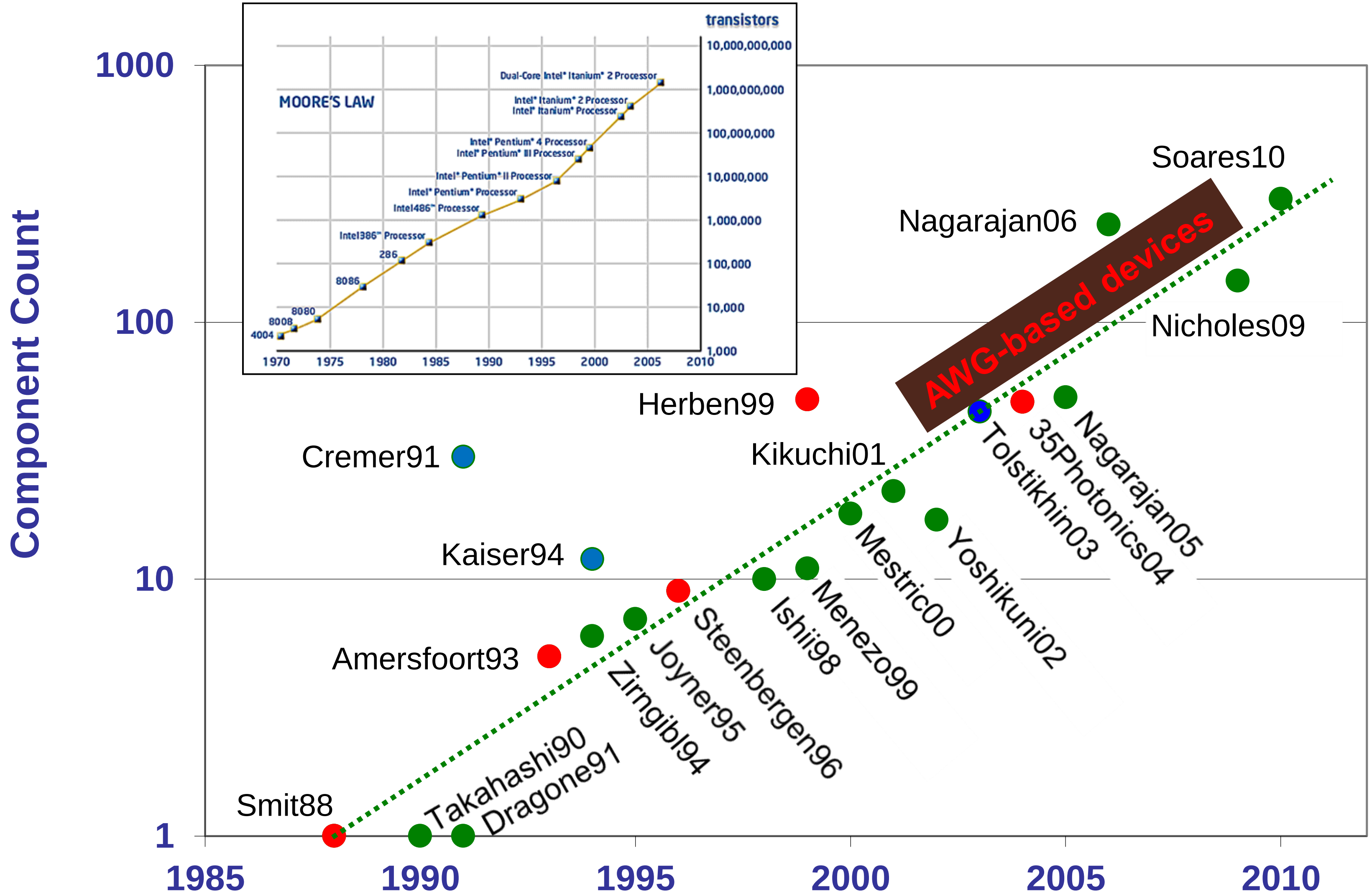


Electric field changes the refractive index and hence the phase change of the optical wave

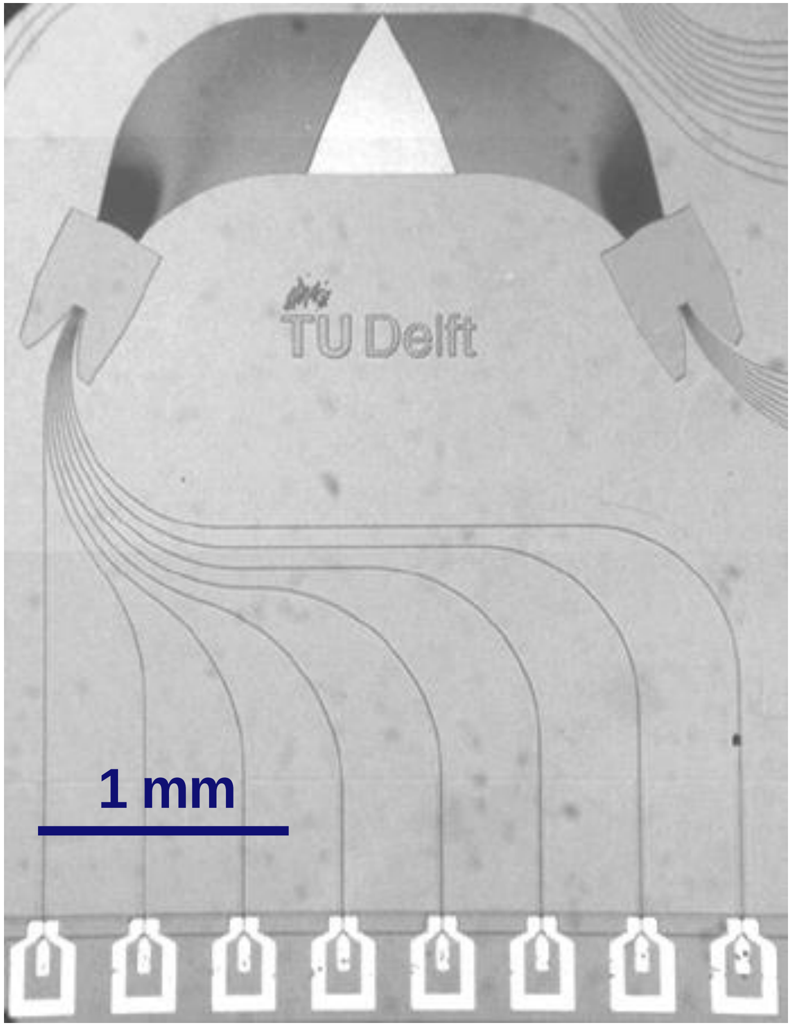
Photonic Integration with basic building blocks



Moore's law for InP based PICs



Moore’s law for InP based PICs



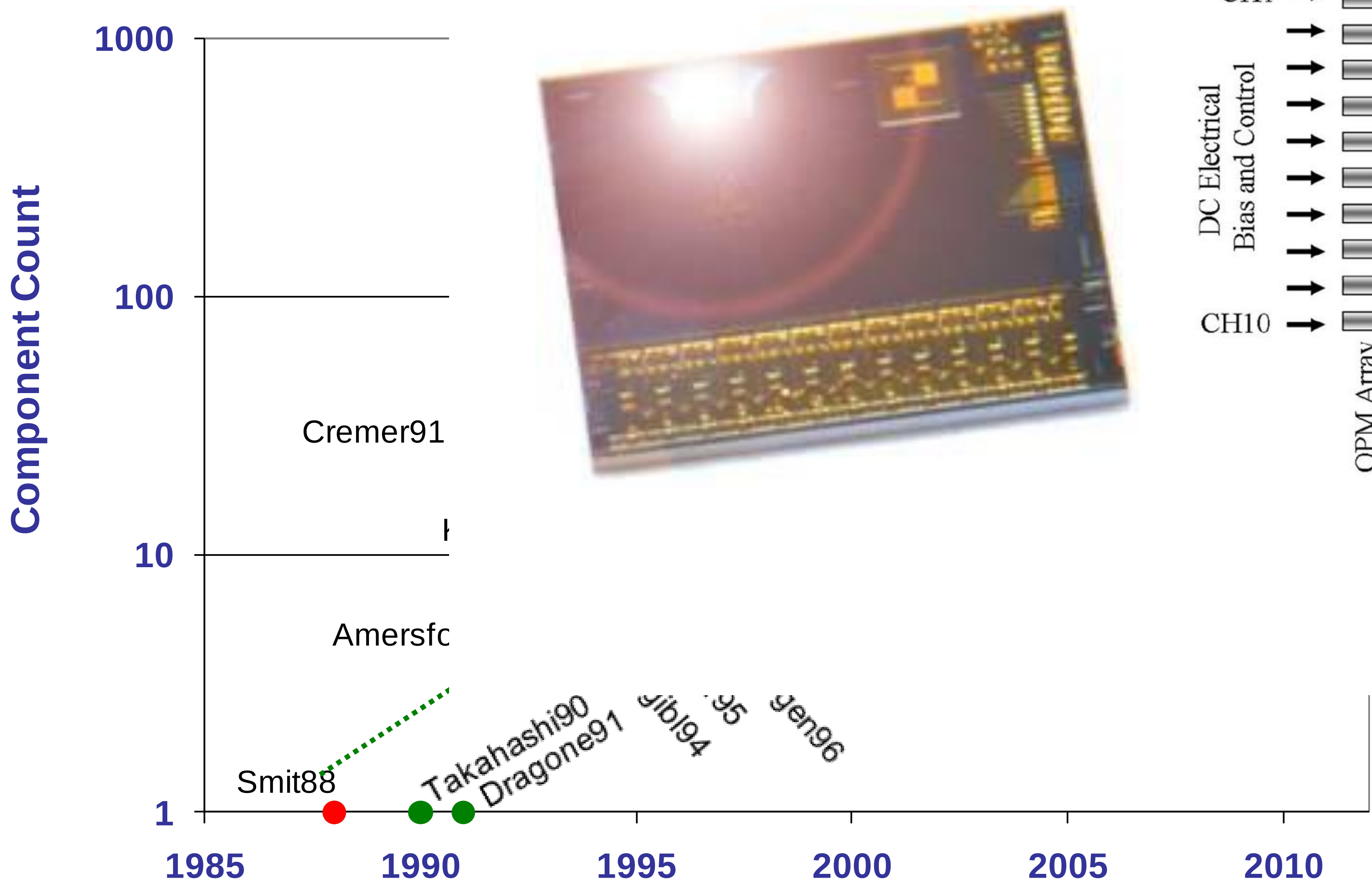
Steenbergen

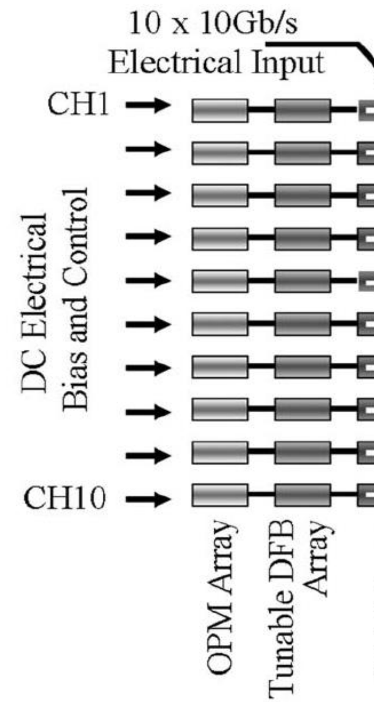
8x20 GHz WDM receiver

PTL, 1996

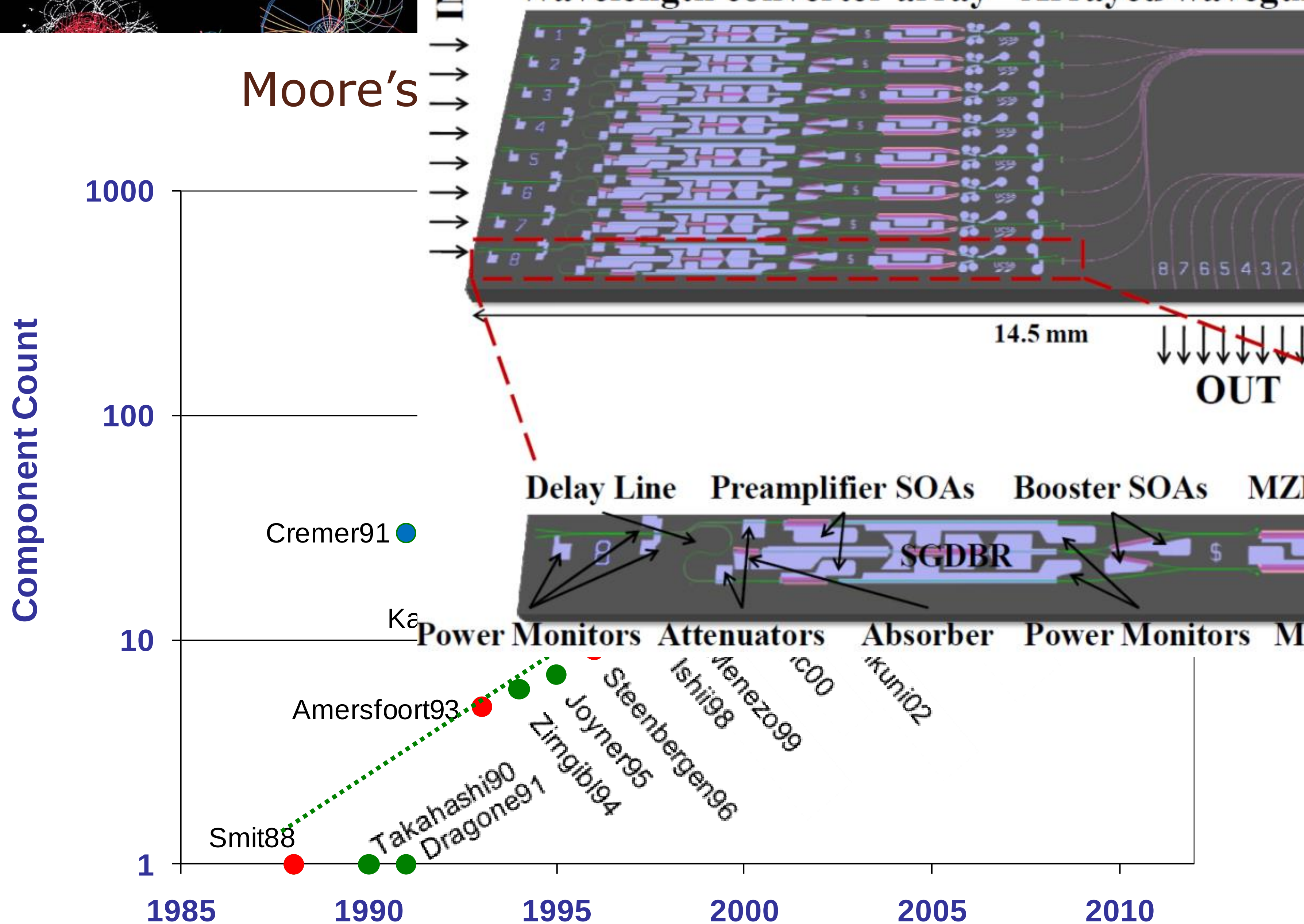
Moore'

Infinira 10x10 Gb/s WDM TRX
2005, 51 components



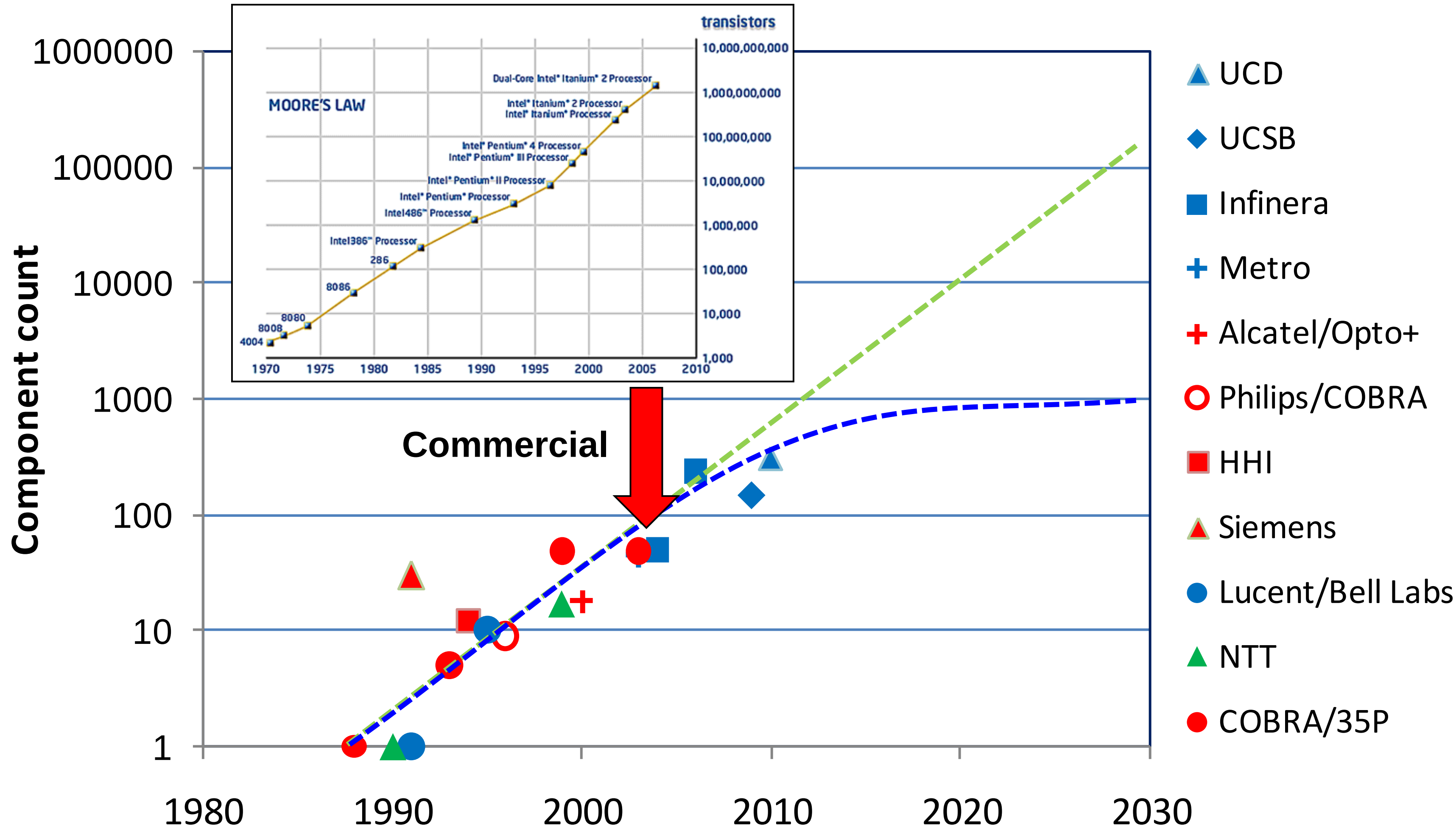


Moore's



Component Count
1000
100
10
1
1985
1990
1995
2000
2005
2010
Cremer91
Ka
Amersfoort93
Smit88
Takahashi90
Dragone91
Zimgibl94
Joyner95
Steenbergen96
Ishii98
Menezo99
Kuni02
14.5 mm
OUT
8 7 6 5 4 3 2
Delay Line
Preamplifier SOAs
Booster SOAs
SGDBR
Power Monitors
Attenuators
Absorber
Power Monitors

What Next?



Advantages : Integrating more functionality, reducing size and reducing cost

Photonic IC Generic Integration platform

Passive	Phase	Amplitude	Polarization
waveguide	phase modulator	optical amplifier	polarization converter

Powerful circuit simulation tools

Application

Powerful layout tools

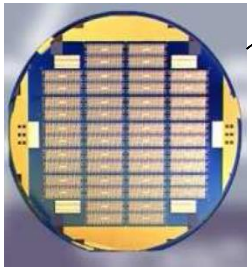
A designer

Designs from designers using the same platform

New design

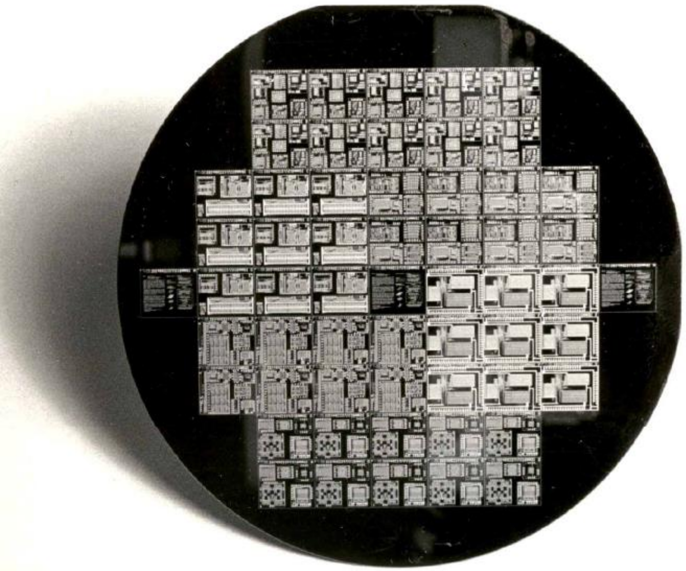
Wafer fab

Multi-project wafer



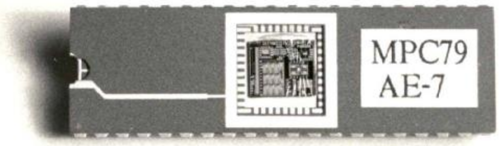
Device back to users

History repeats itself…

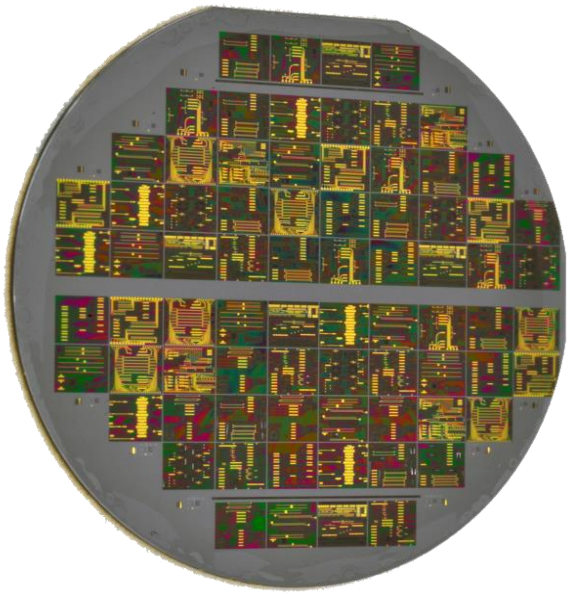


Silicon electronic ICs

1979

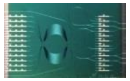


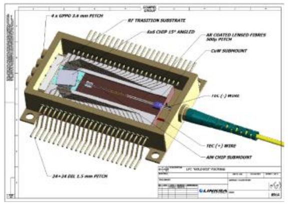
MPC79, Lynn Conway



Indium phosphide photonic ICs

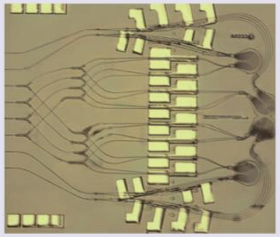
2012





Examples of ASPICs and applications

Optical switching

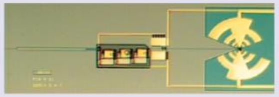


4x4 space and wavelength selective switch

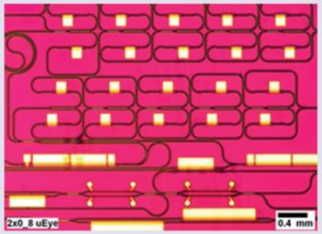
Fast optical switch matrix

QPSK receiver

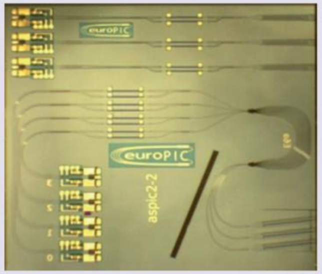
THz Optical to RF converter



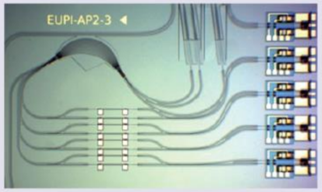
Fiber sensor readout



Brillouin strain sensor readout

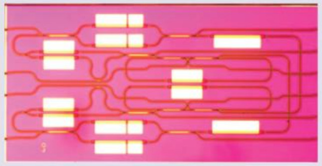


Fiber Bragg Grating readout



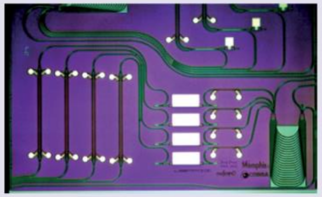
Fiber Bragg Grating readout

Variety of lasers



Widely tunable ring laser

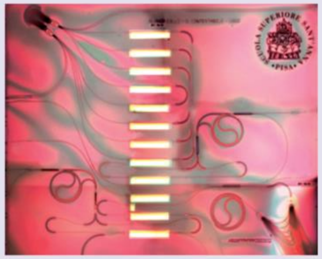
Variable repetition rate pulse laser



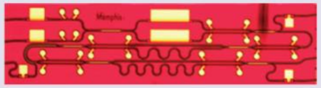
Filtered-feedback multi-wavelength laser

tunable laser with integrated MZI modulator

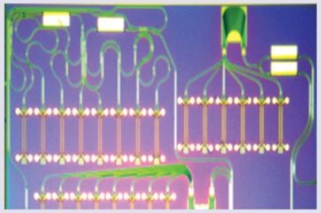
Optical data handling



All-optical regenerator for constant envelope WDM signals

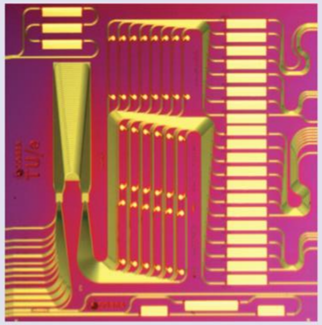


WDM to TDM Trans-Multiplexer

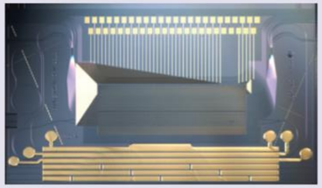


Pulse serialiser

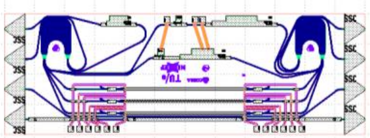
Medical and bio-imaging

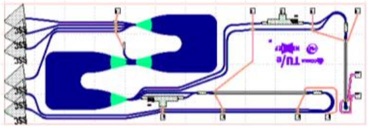


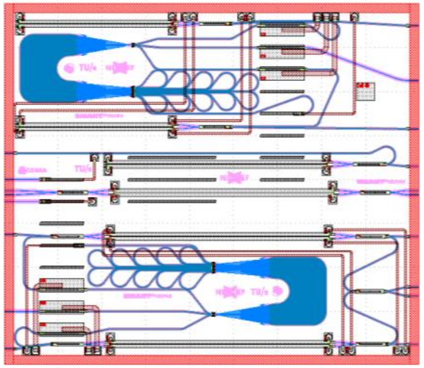
Pulse shaper for bio-imaging

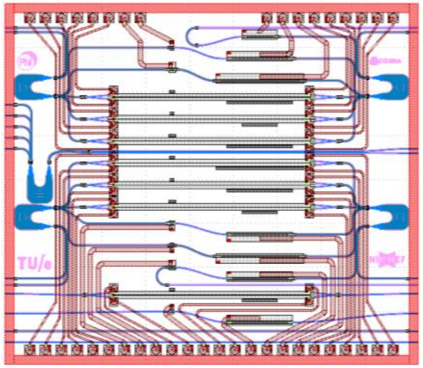


Integrated tunable laser for optical coherence tomography



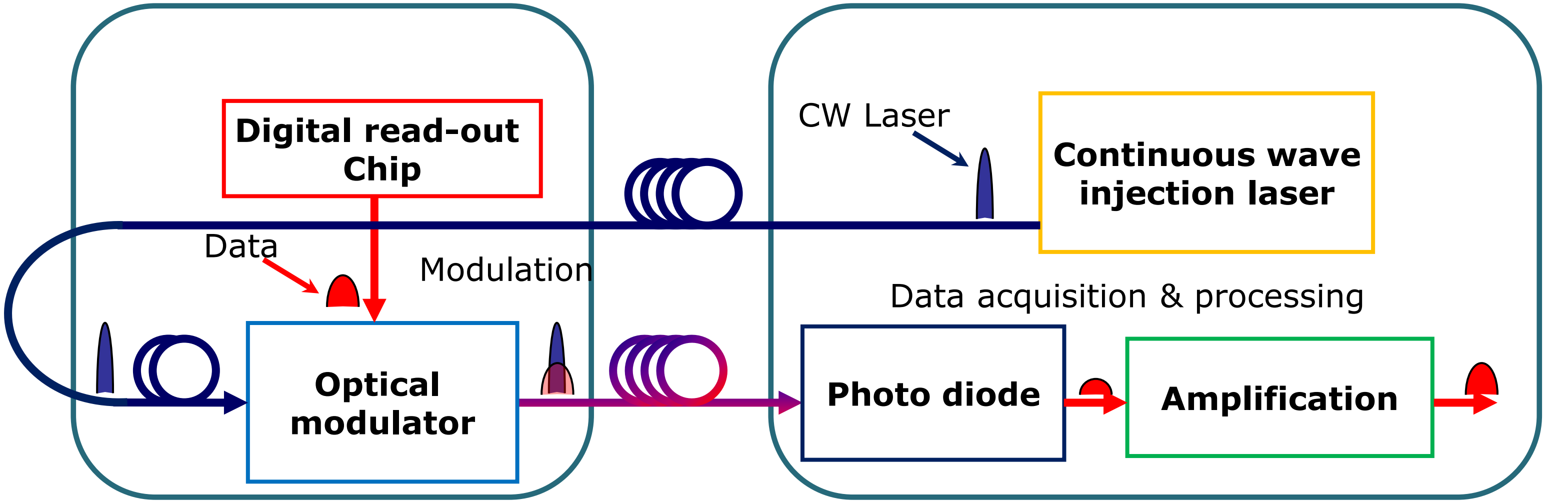


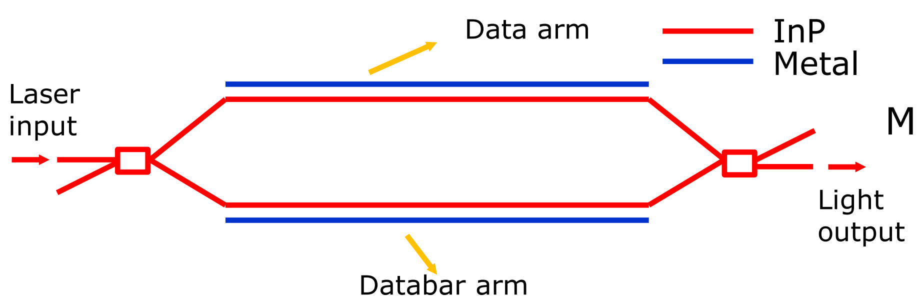




External modulation technique

- Modulators form the heart of the external modulation technique.

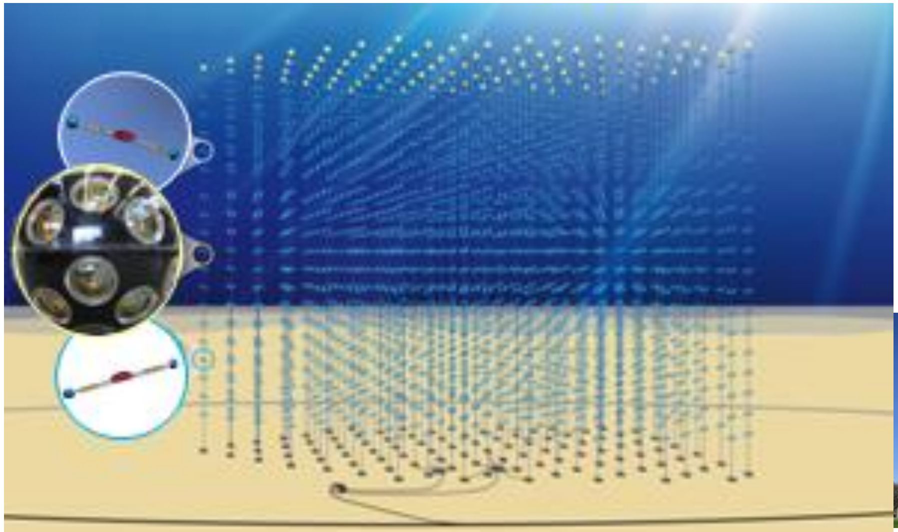


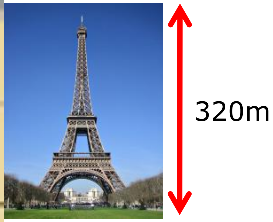


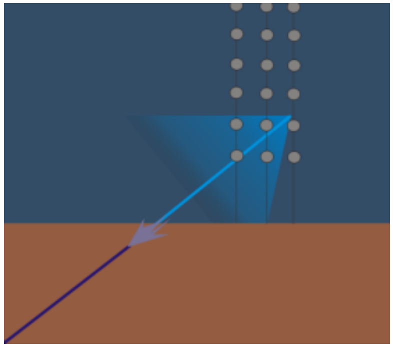
Mach Zehnder (MZ) Modulator

KM3NeT Detector concept

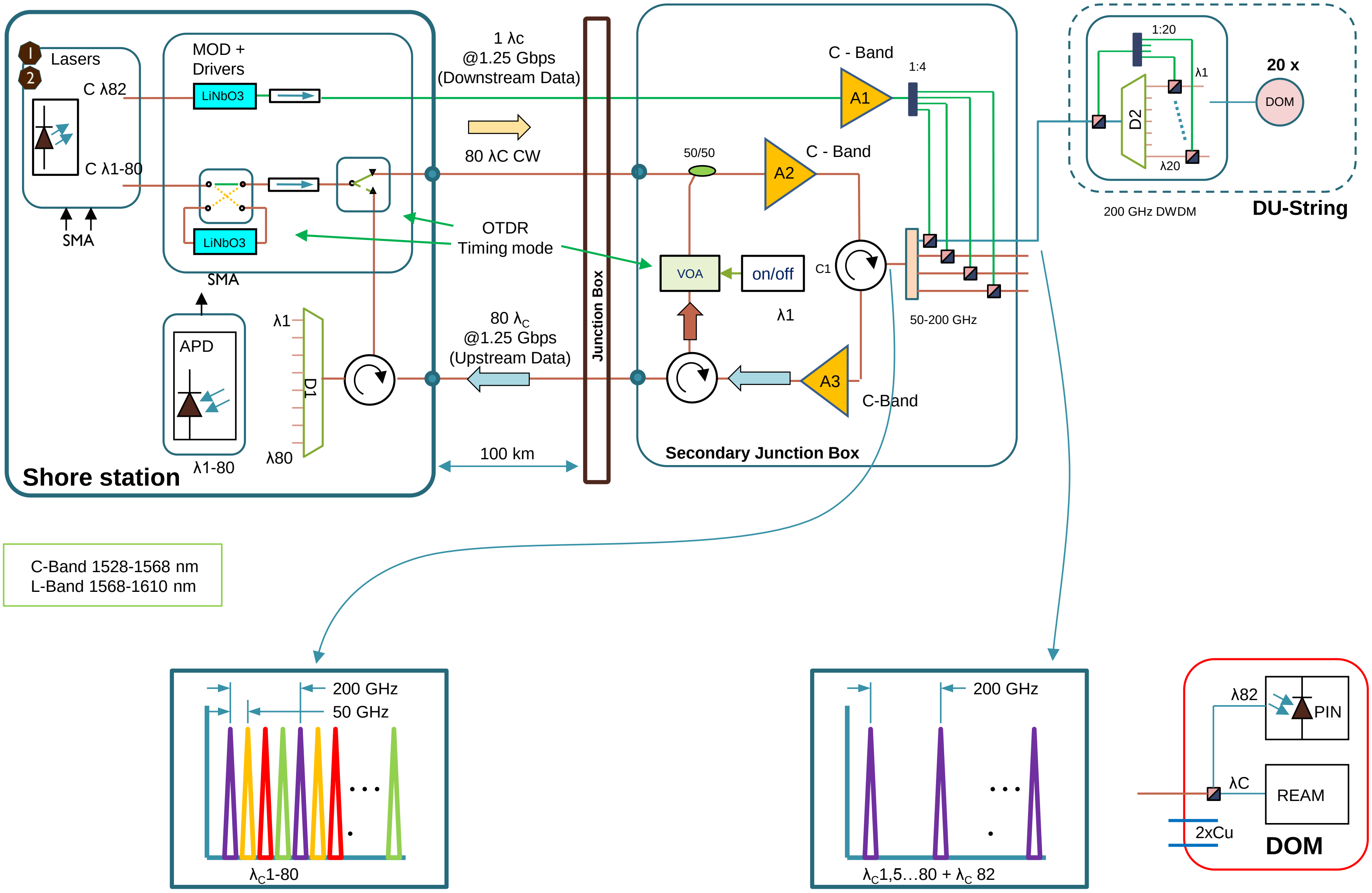
- KM3NeT is a cubic kilometer neutrino telescope to be installed in the Mediterranean sea. For more information : www.km3net.org
- High density data readout in remote submarine conditions.
- Savings in area, cost and power motivate innovation, research and development of ASPICs.







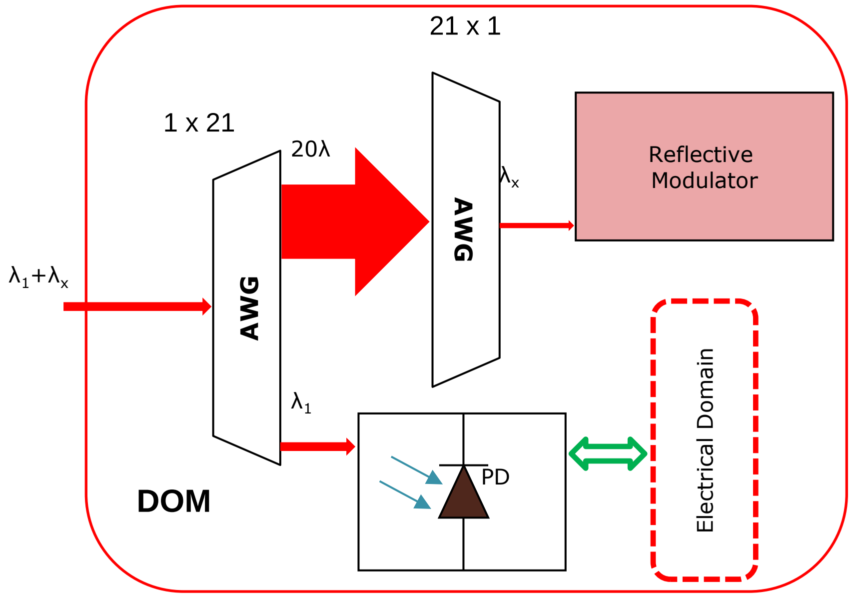
Concept for 80 Channels with Overlay DWDM*



*R&D on high density data readout. Explored as an option - Not used in the project presently.

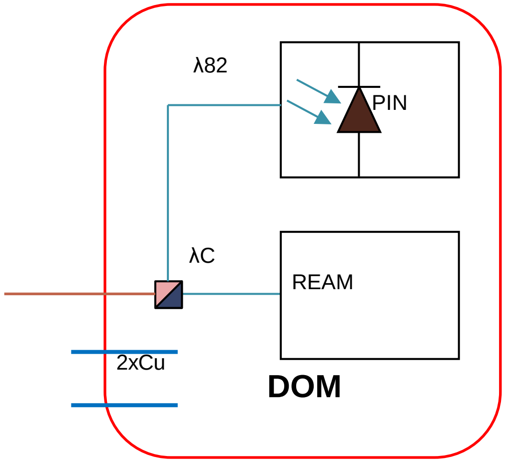
InP based Colorless transceiver for KM3NeT

- Continuous wave light (one of the 20 wavelengths separated at 200 GHz) is separated from the slow control data.
- The slow control data is detected by the photodiode and provided to the electronics.
- The data from the sensors (effective data rate ~1.25 Gbps upstream) modulates the CW light and is reflected.
- Aim is to integrate the building blocks (AWG, Modulator and PD) on a single die.

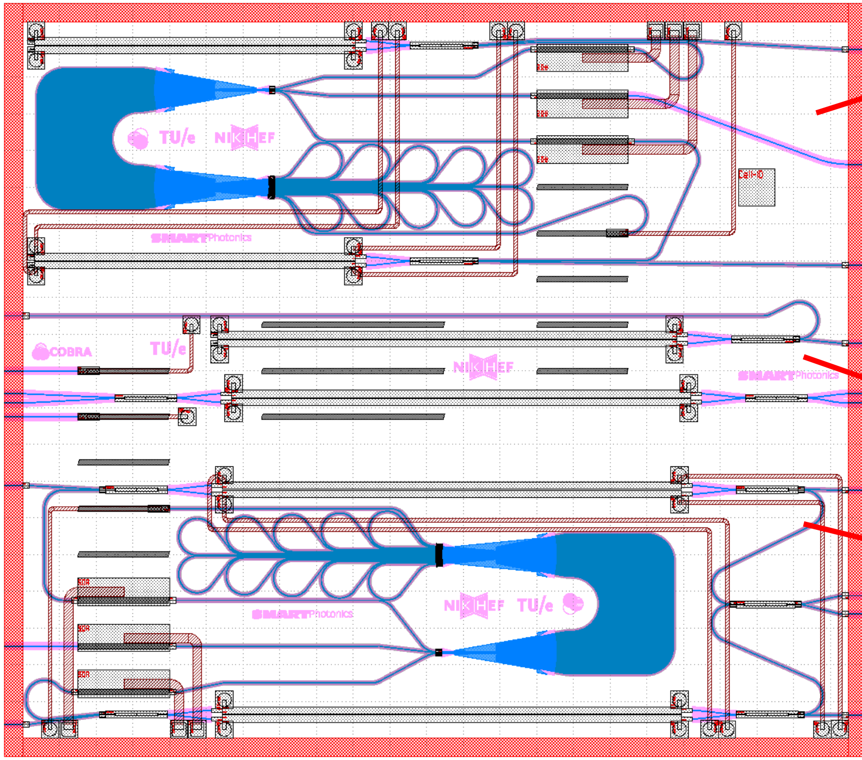


λ_x can be any of the 20 wavelengths

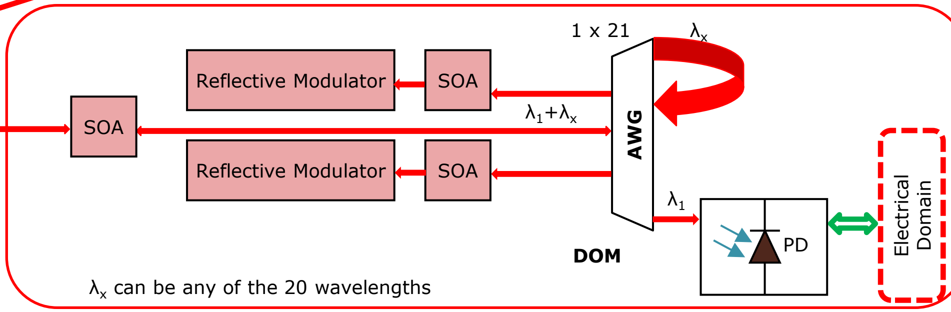
will replace



InP based Colorless transceiver for KM3NeT

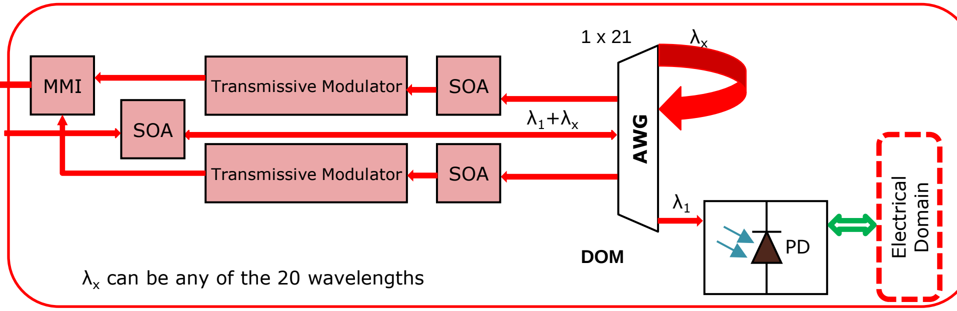


Reflective circuit



Test structures

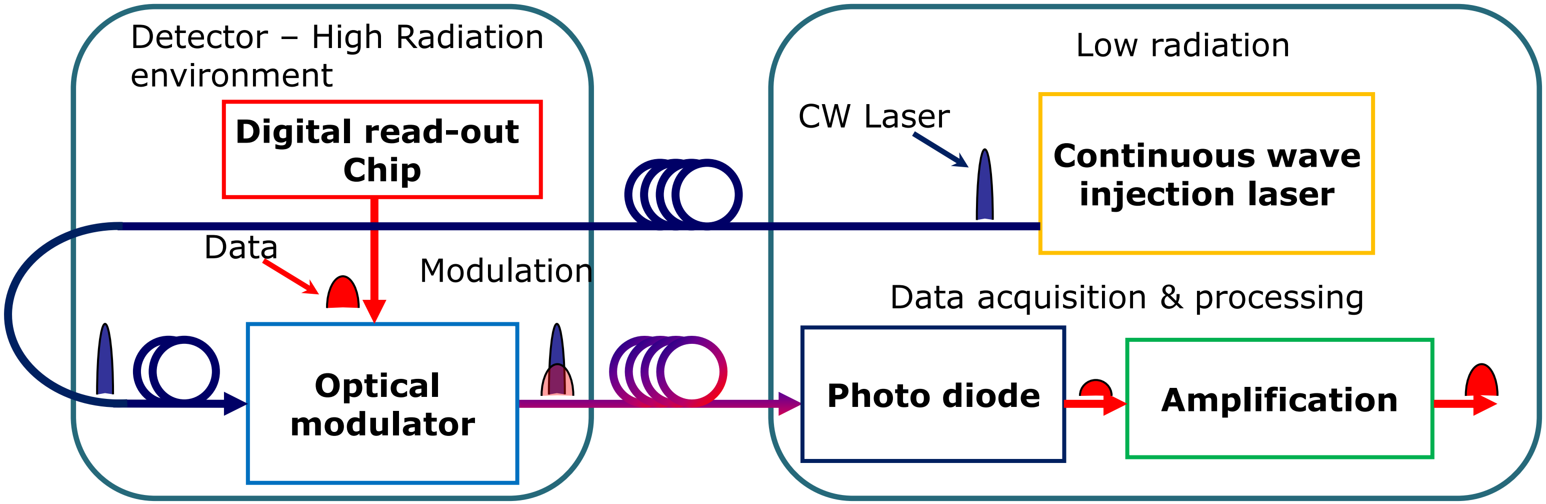
Transmissive circuit

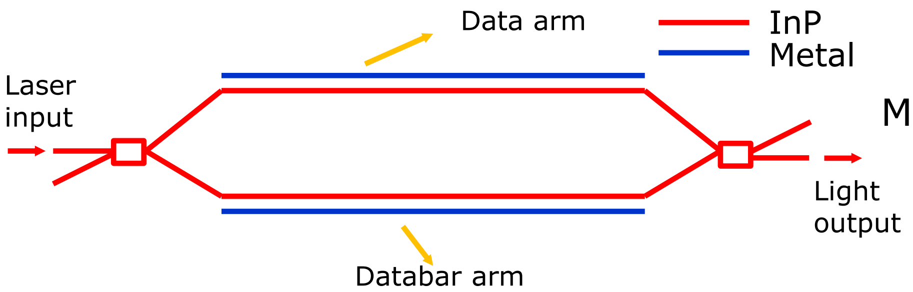


- AWGs channel spacing is dependent also on processing. With a loop back architecture, we remove the process variations on the AWG.
- Transmissive architecture can be used for testing purposes.

ASPICs for High Energy Physics Experiments

- Modulators form the heart of the external modulation technique.
- Little is known about radiation hardness of (InP) modulators. Ultimate goal : application at inner detectors at HL LHC.

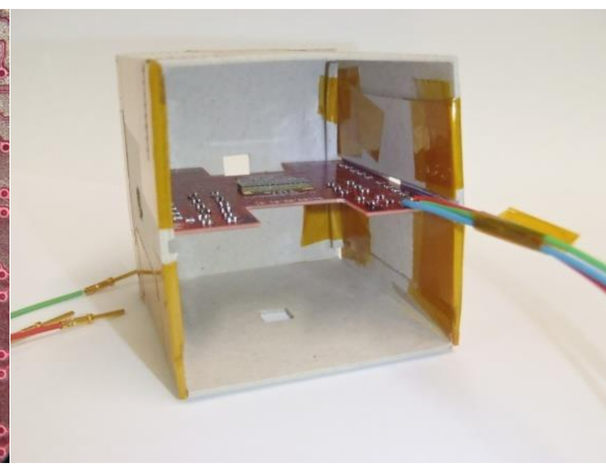


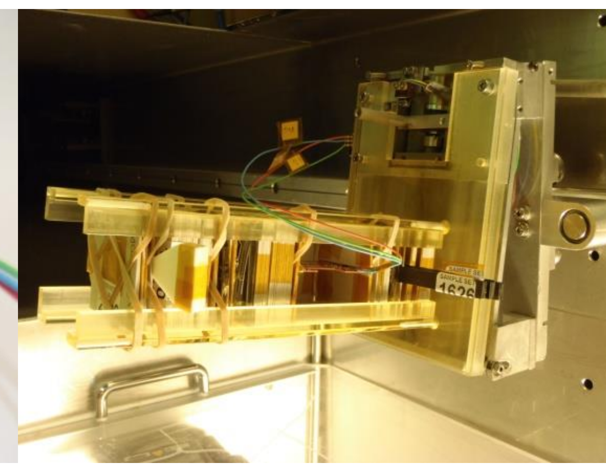


Mach Zehnder (MZ) Modulator

Beam Test of InP based MZ modulators

- Samples mounted in a shuttle that moves in and out of the 24 GeV/c proton beam at CERN to 1E12, 1E13, 1E14 and 1E15 p/cm2.
- Vertex detectors at HL-LHC require a radiation hardness ~ 1E16 p/cm2.
- The sample contains 22 modulators and measures 14mm × 4 mm

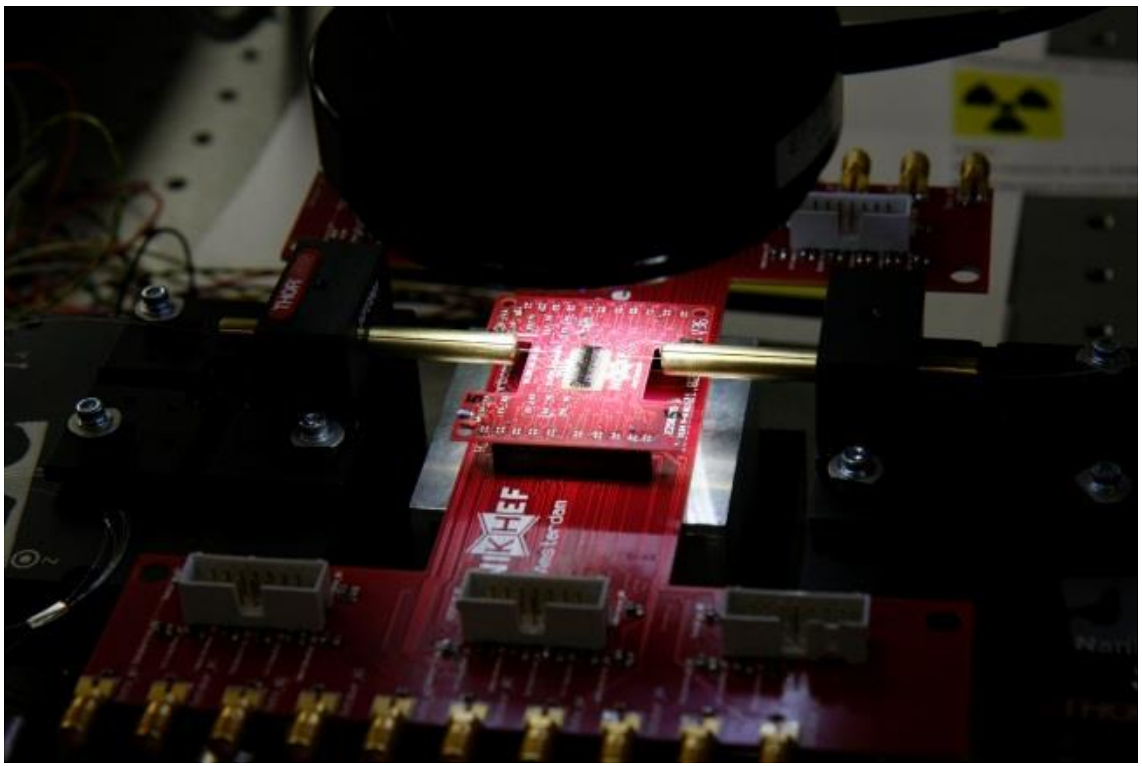




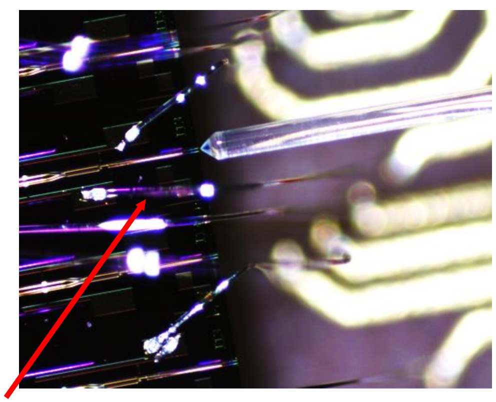
Submount dimensions : 48 mm × 42 mm

Measurements of photonic chips

- Measurements need precision alignment of chips and fibers.
- Lensed fibers are used to couple and collect light.
- Alignment of fibers are done manually using manipulators.



Lensed fiber (9 u core) to be aligned to a 2 u wide 1u high waveguide.



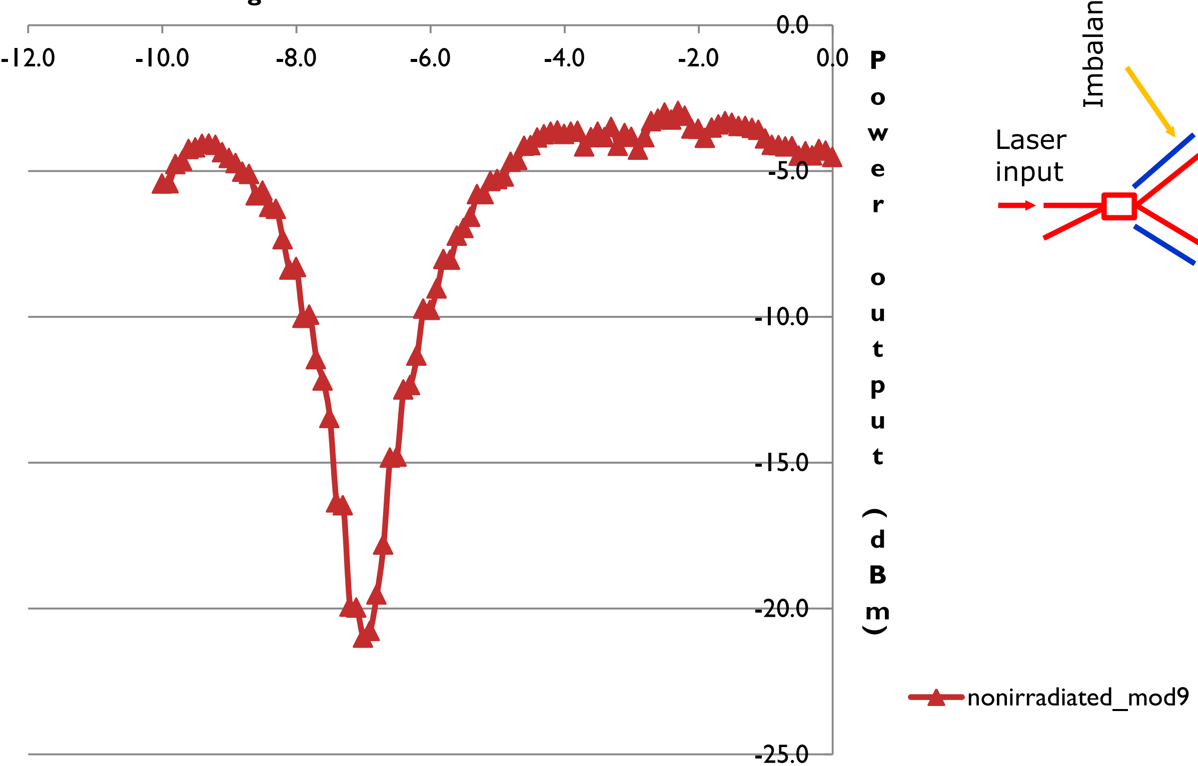
Bond wire

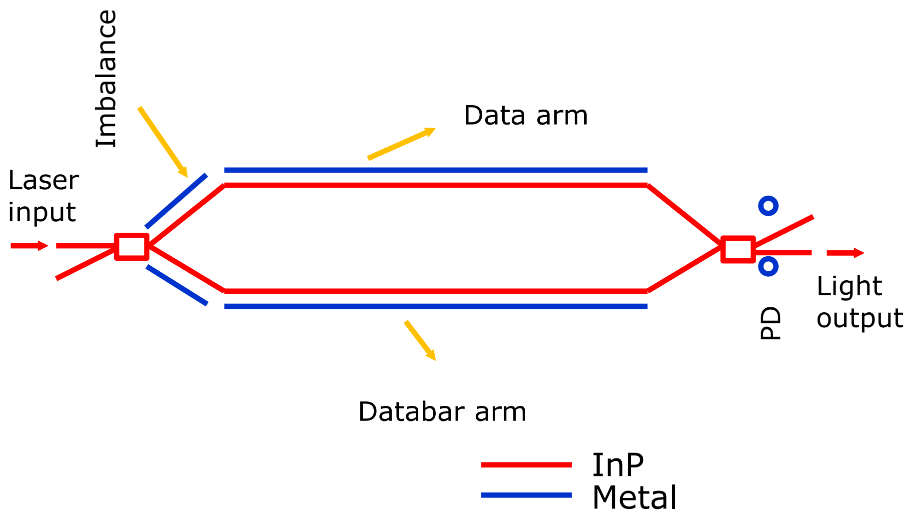
A Sample measurement

Input power = + 6dBm @ 1550nm
Y axis – Power (dBm) measured at the output.
X axis – Voltage scan on one of the arms of the modulator.

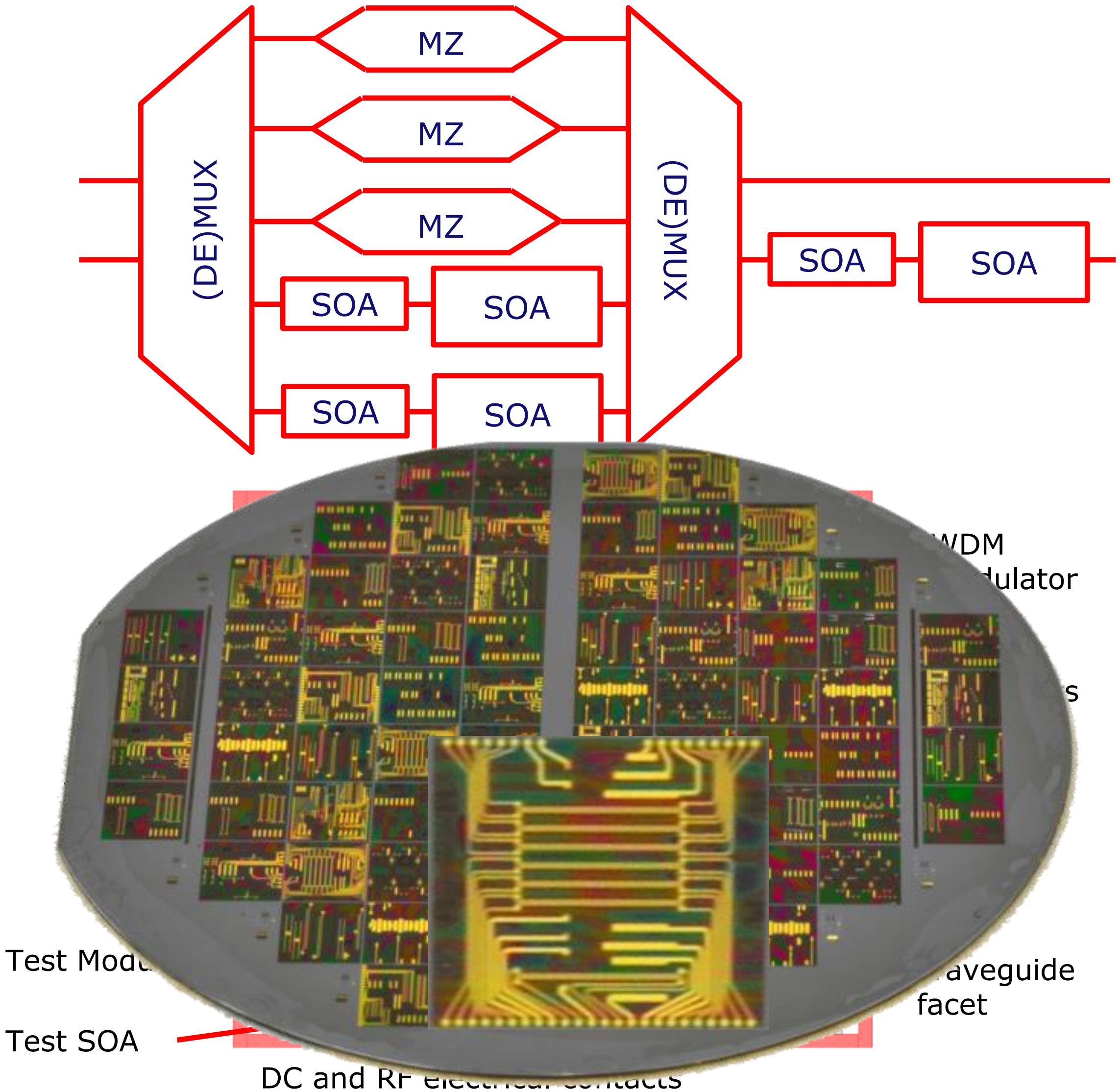
Non-Irradiated samples

Reverse Scan voltage on one of the arms of the Modulator



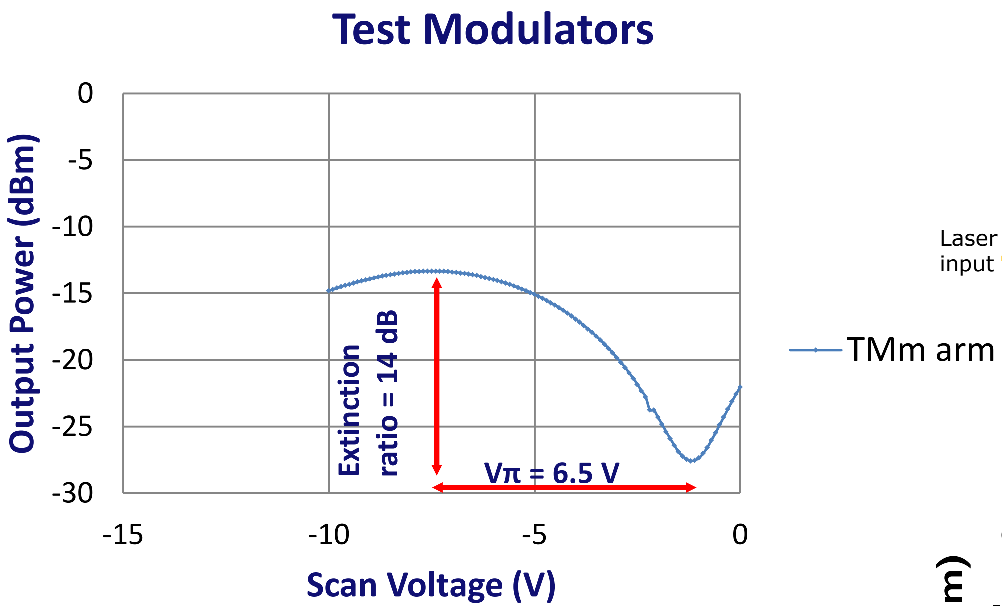


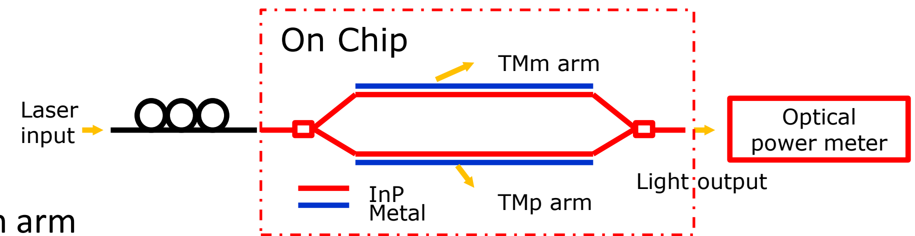
WDM Modulator in the COBRA6 run

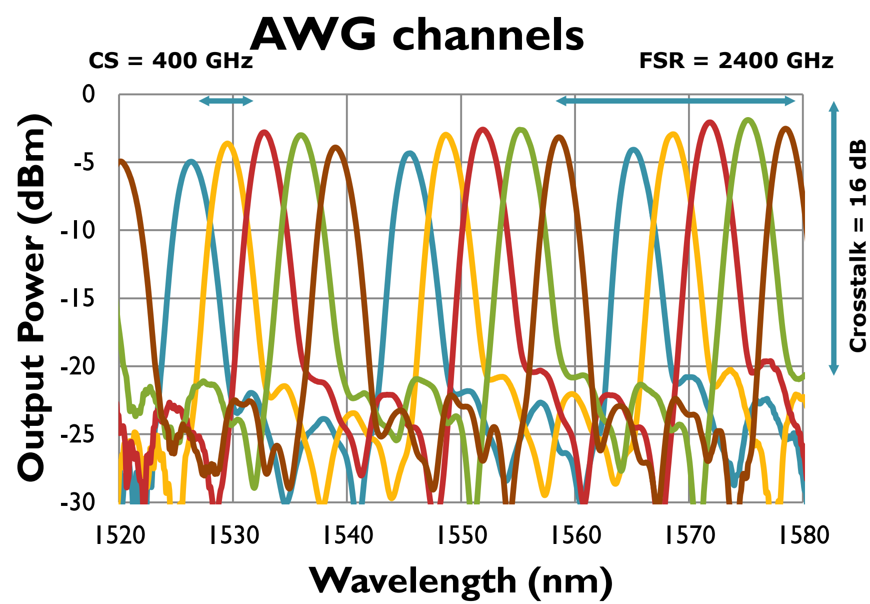


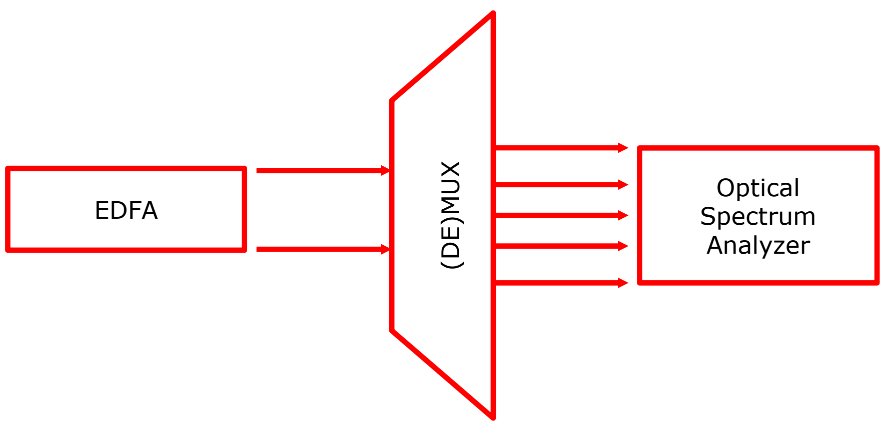
- MZ modulators:
  - 2 mm phase sections
- Two 2×5 AWGs:
  - $\Delta\lambda = 400$ GHz
  - $\mathrm{FSR} = 2400$ GHz
- Amplifiers:
  - small: modulation
  - large: gain
- Test structures:
  - separate building blocks

Preliminary Measurement results









Conclusions and Future

- Photonic Integration is in it’s nascent stages and holds a ‘bright’ future.
- Physics experiments can benefit from custom ASPICs.
  - Smaller, low power, more functionality, cheaper for large quantities
- Generic Photonic Integration platform and access to MPW runs makes it easier for designing ASPICs for High Energy Physics.
- Lot to be designed and measured, long way to go…