PHOTONICS RESEARCH GROUP

GHENT UNIVERSITY

imec embracing a better life

Introduction to Silicon Photonics

Wim Bogaerts

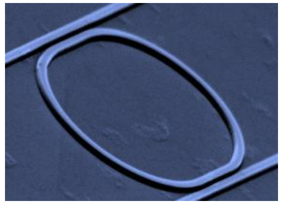
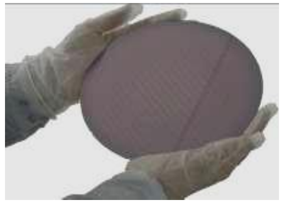
INFIERI Summer School – 3 September 2021

UAM Universidad Autónoma de Madrid

INFIERI

6th Summer School on INtelligent signal processing for FrotIEr Research and Industry

Photonics Research Group


Research Group of Ghent University

- Faculty of Engineering and Architecture
- Department of Information Technology (INTEC)
- Associated laboratory of IMEC
- Member of the Center for Nano- & Biophotonics (NB photonics)

Technology Research

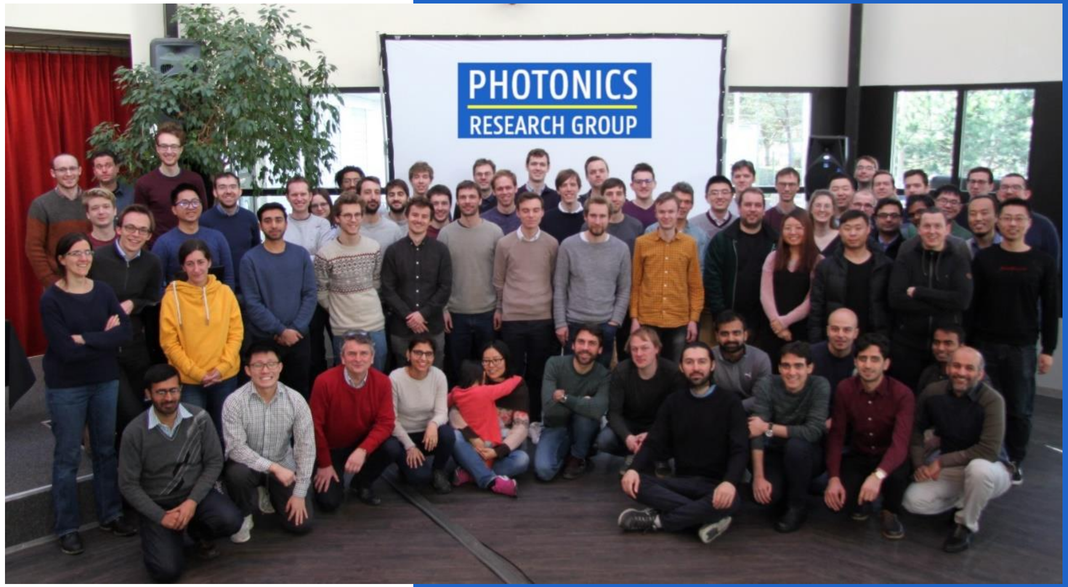
- Photonic Integrated Circuits: light on a chip
- On silicon: “Silicon Photonics”
- Enhanced with new materials: III-V, ferro-electrics, graphene, …

Applications

- High-speed telecom and datacom
- Sensing for life sciences: visible and Mid-IR
- Optical information processing

11 Professors
16 postdocs
50 PhD students
10 support staff

20+ nationalities
7 ERC grants
6 spin-off companies
50 journal papers/year
Class 100 clean rooms
M.Sc. Photonics program



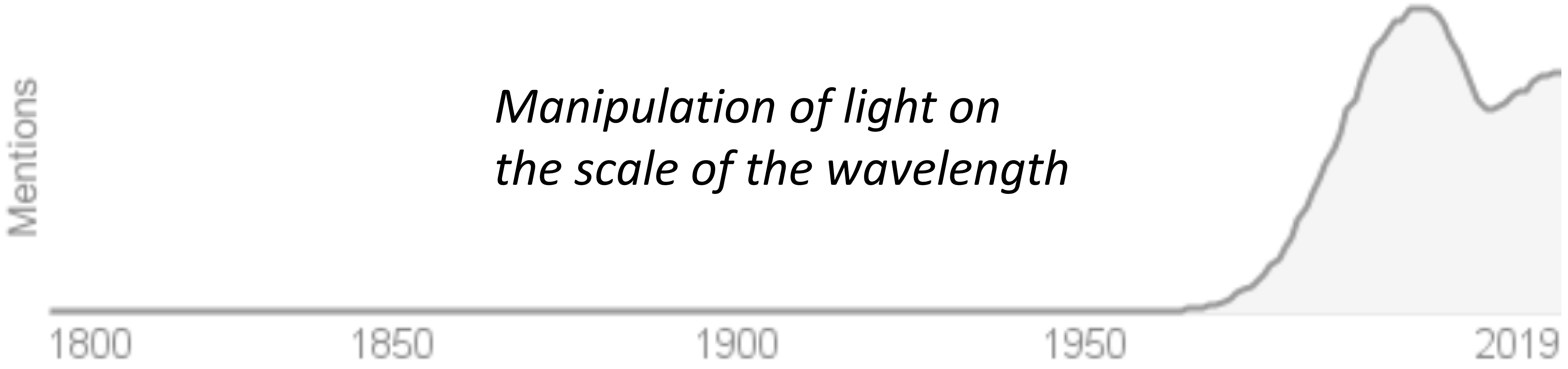
WHAT'S IN A NAME?

nanophotonics (noun)

the branch of technology concerned with the properties and transmission of photons, for example in fibre optics *(Oxford Dictionary)*

Photonics is the physical science and application of light generation, detection, and manipulation through emission, transmission, modulation, signal processing, switching, amplification, and sensing.
(Wikipedia)

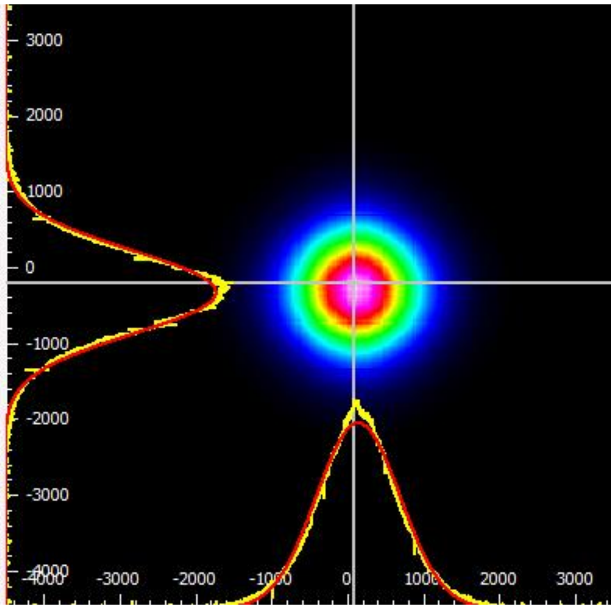
Manipulation of light on the scale of the wavelength

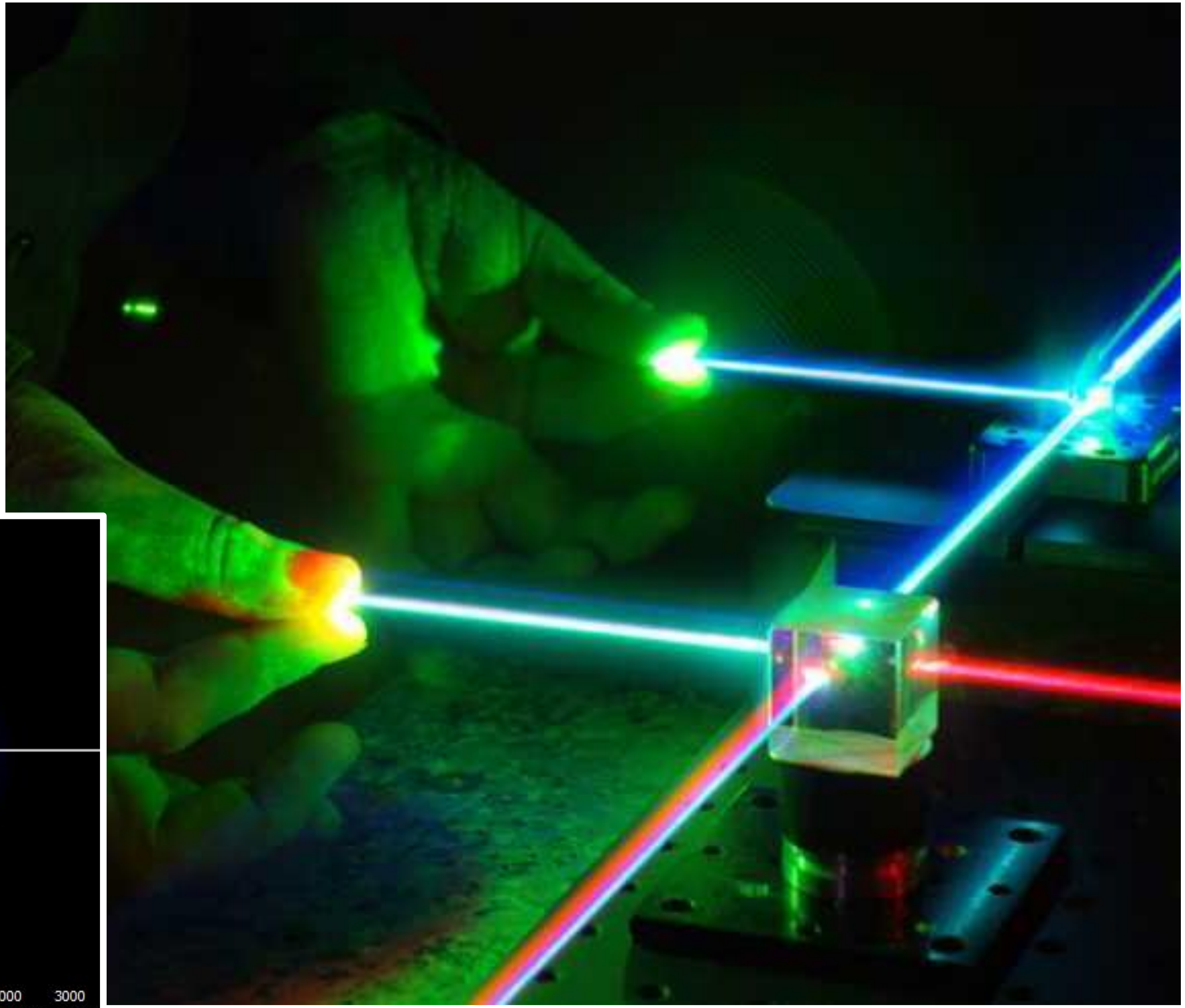


Manipulating Beams of Light

Beams of light contain information

- Total power
- Intensity profile
- Phase profile
- Wavelength
- Polarization



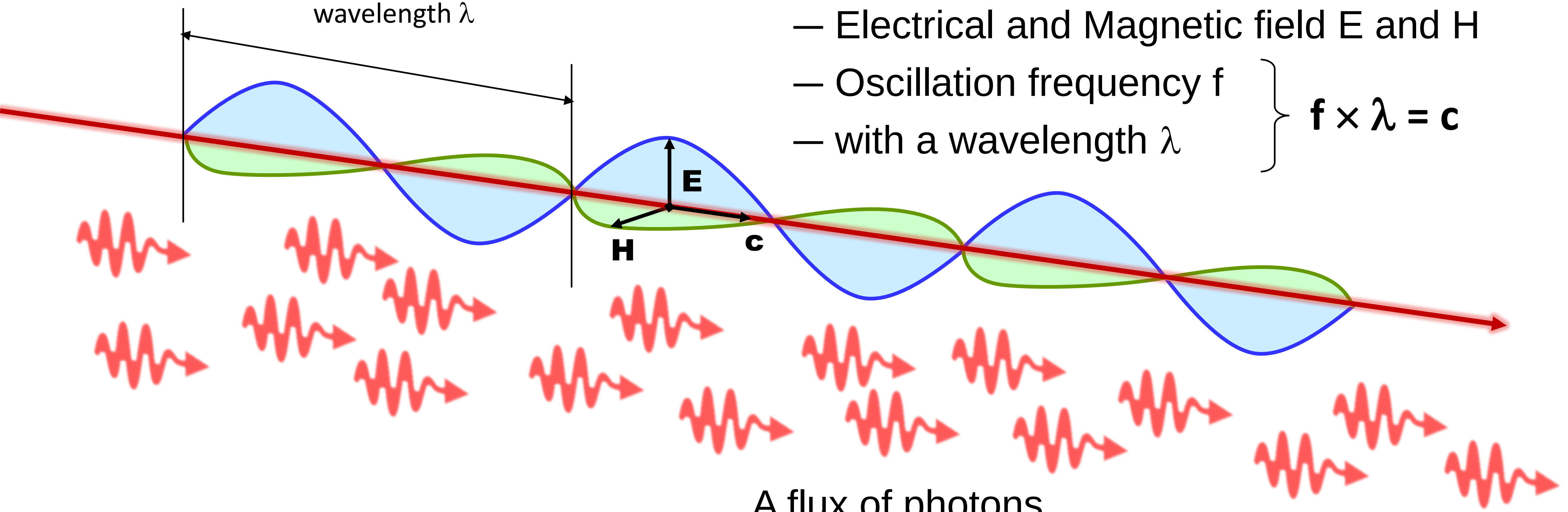


What is Light?

An electromagnetic wave

- Propagates at speed of light c
- Electrical and Magnetic field E and H
- Oscillation frequency f
- with a wavelength λ

$$f \times \lambda = c$$



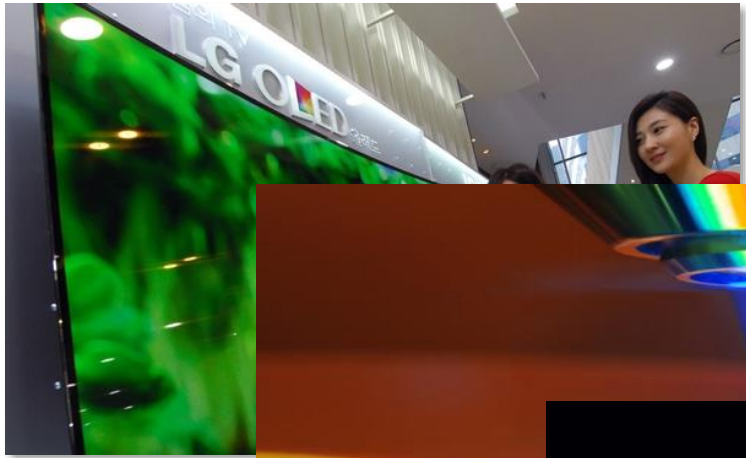
A flux of photons

- with energy E = *h*.f

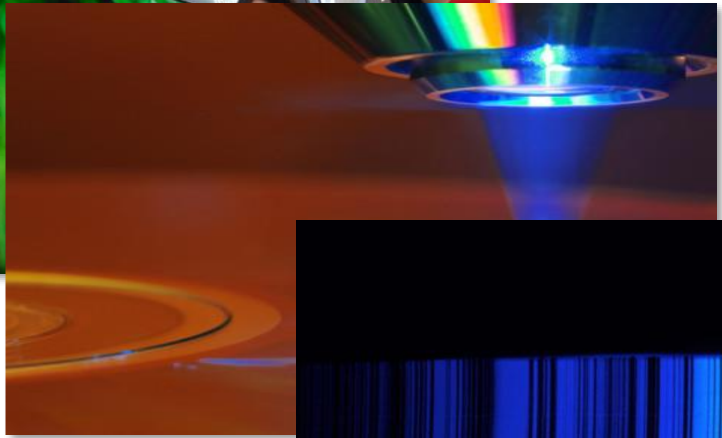
PHOTONICS: SCIENCE AND ENGINEERING WITH LIGHT

What is light used for?

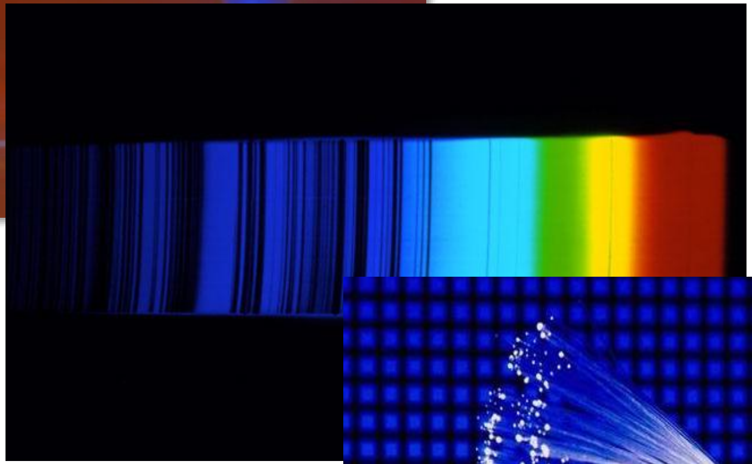
- material processing
- displays and lighting
- communication fiber optics
- sensing
- computing?



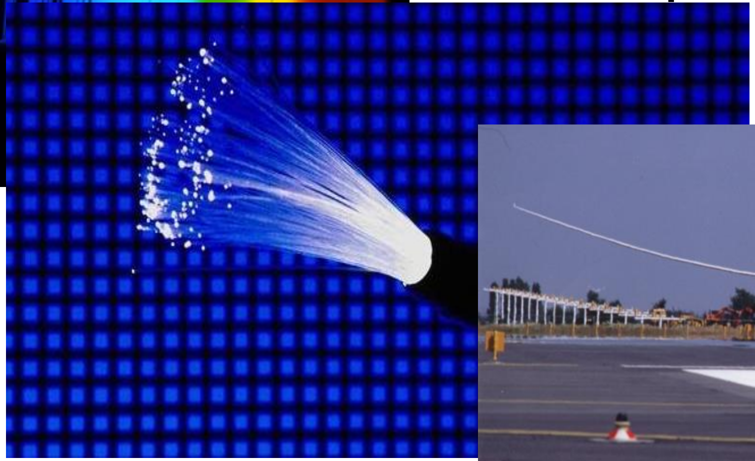
Displays



Data Storage



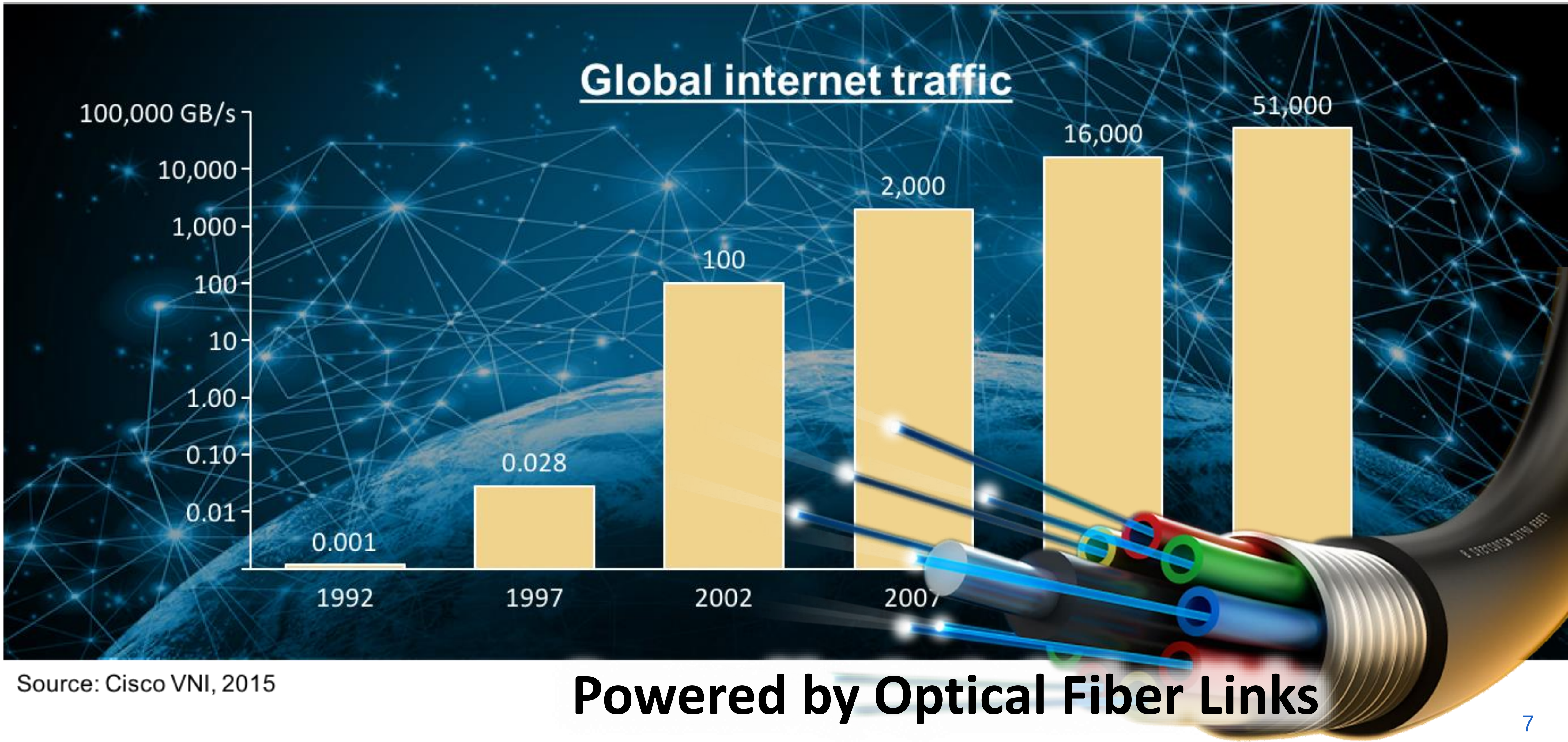
Spectroscopy



Communication

Sensing

KEY DRIVER OF PHOTONICS TODAY: COMMUNICATION



Source: Cisco VNI, 2015

Powered by Optical Fiber Links

OPTICAL COMMUNICATION IS NOT NEW

source:Sean D'Souza

OPTICAL COMMUNICATION: 18TH CENTURY 'CHAPPE'

The Semaphore: Packet-switched relay network

ELECTRICAL COMMUNICATION: THE DOWNFALL OF OPTICS?

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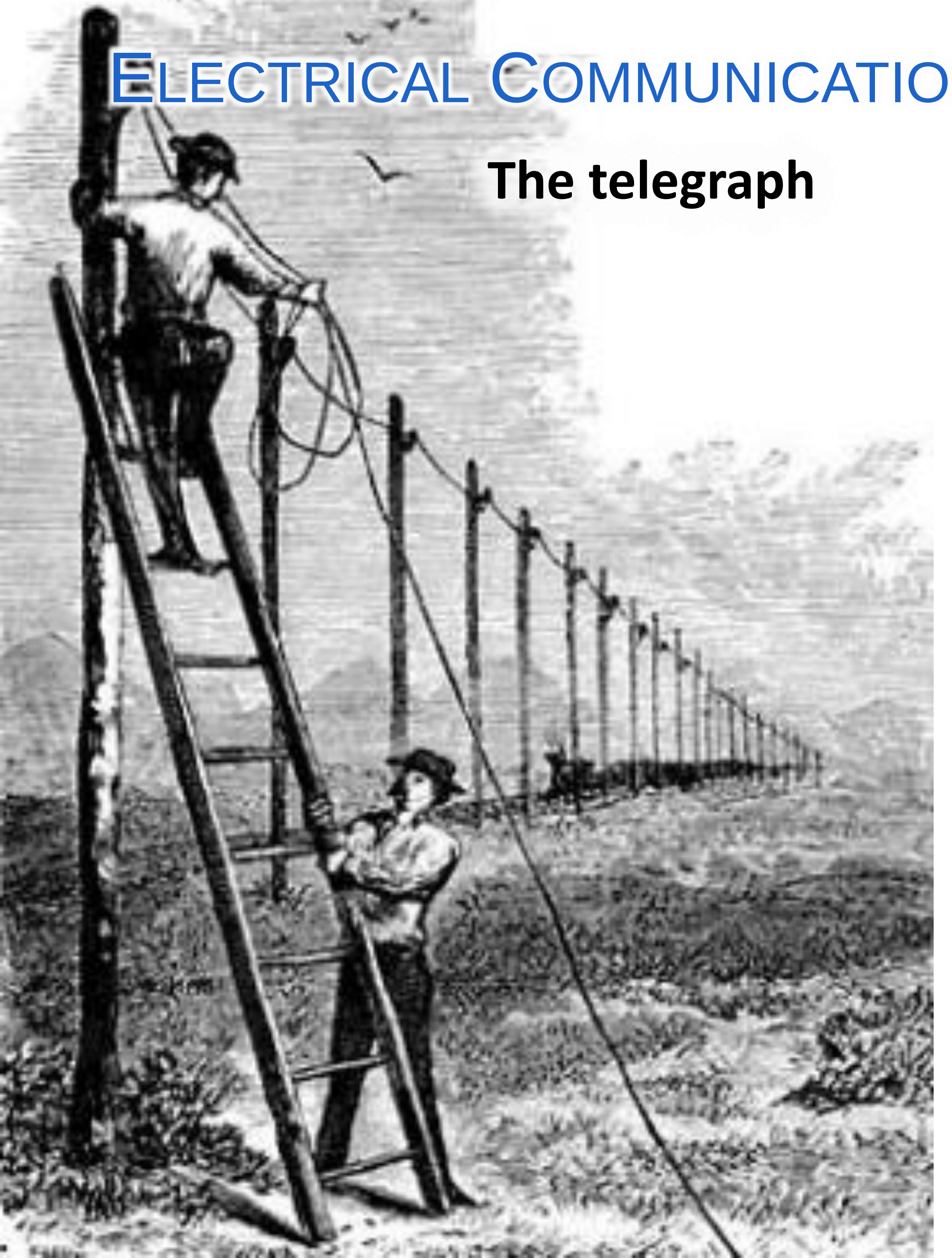
The telegraph



source: Jason Salmon/Shutterstock.com

The "wireless"

1960: THE LASER

A new light source:

- One wavelength
- High power
- High-quality beam

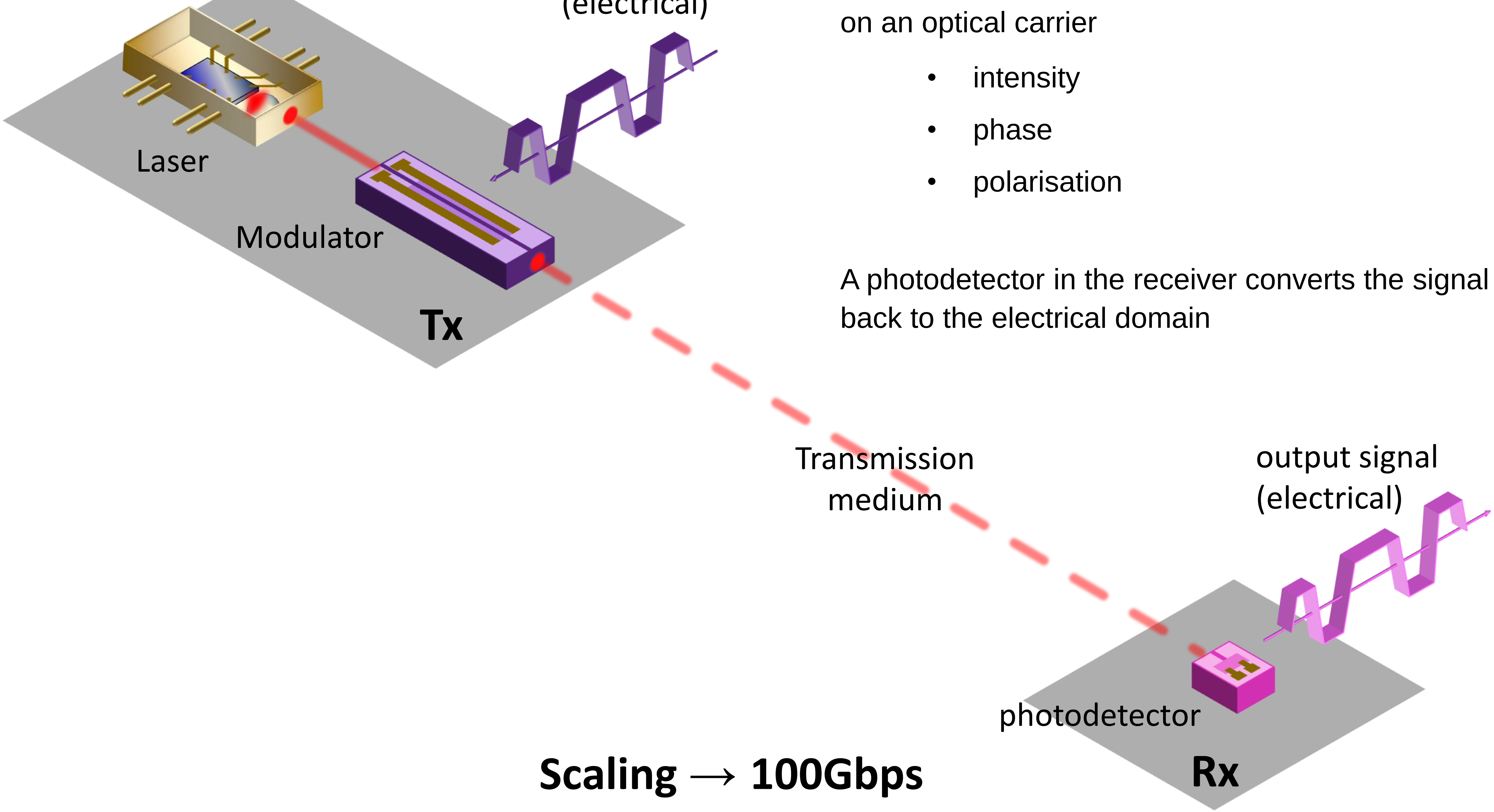
1962: Laser Diode
(Hall, Nathan)

source: Osram

1960: First Laser (Maiman)

source: HRL

AN OPTICAL LINK



Electrical signal is modulated on an optical carrier

- intensity
- phase
- polarisation

A photodetector in the receiver converts the signal back to the electrical domain

Scaling → 100Gbps

But: the problem with light

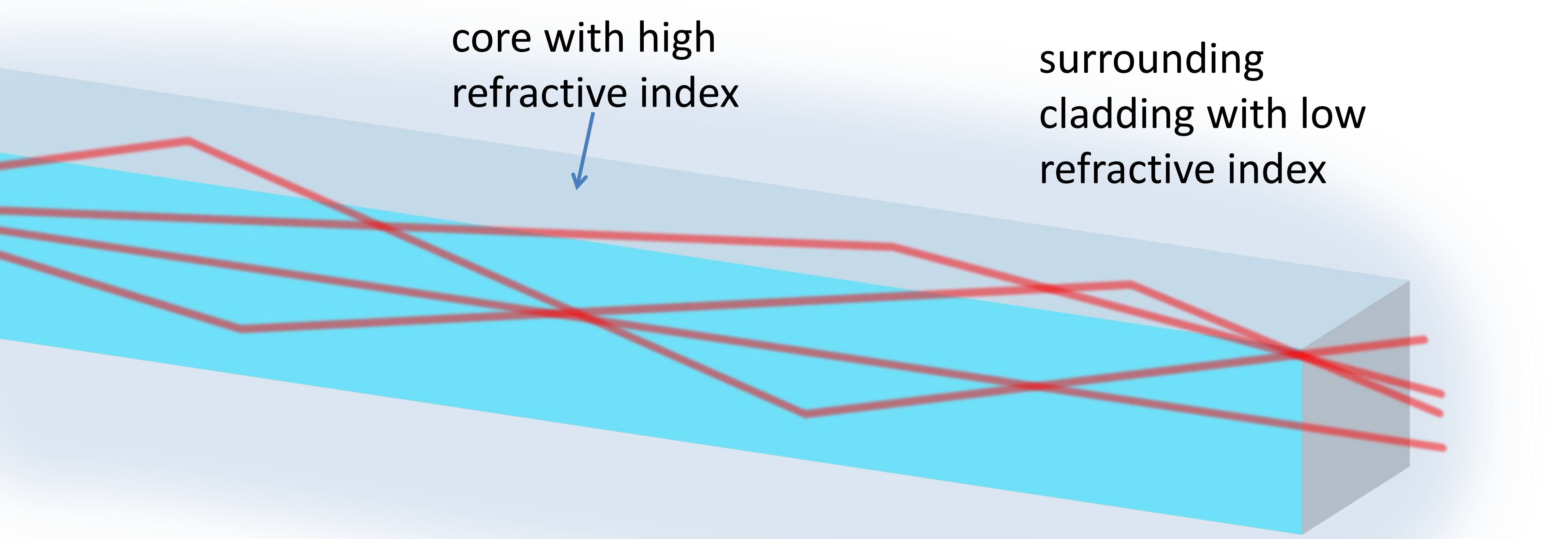
Light travels in straight lines

Manipulate with

- lenses
- mirrors

Not scalable, difficult alignment

OPTICAL WAVEGUIDE



Optical waveguides:

light is confined in a dielectric core of

of high refractive index

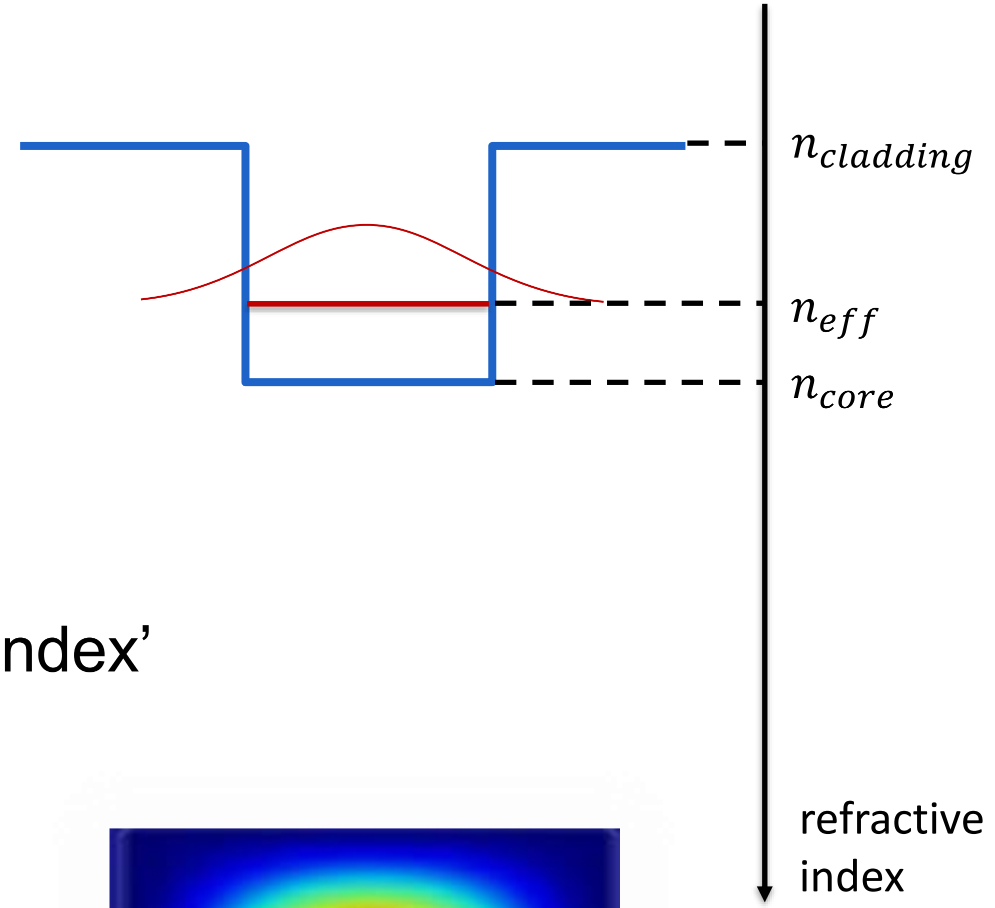
Waveguide = Potential well for photons

Light prefers to reside in a material with high refractive index

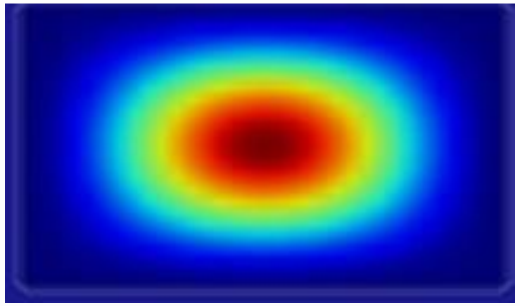
Solution of Maxwell's equation:

- Sine/cosine in the core
- Decaying exponential outside

There is an optical field outside the core!!!



Discrete mode(s) with 'effective refractive index'



WAVEGUIDE = POTENTIAL WELL FOR PHOTONS

Light prefers to reside in a material with high refractive index

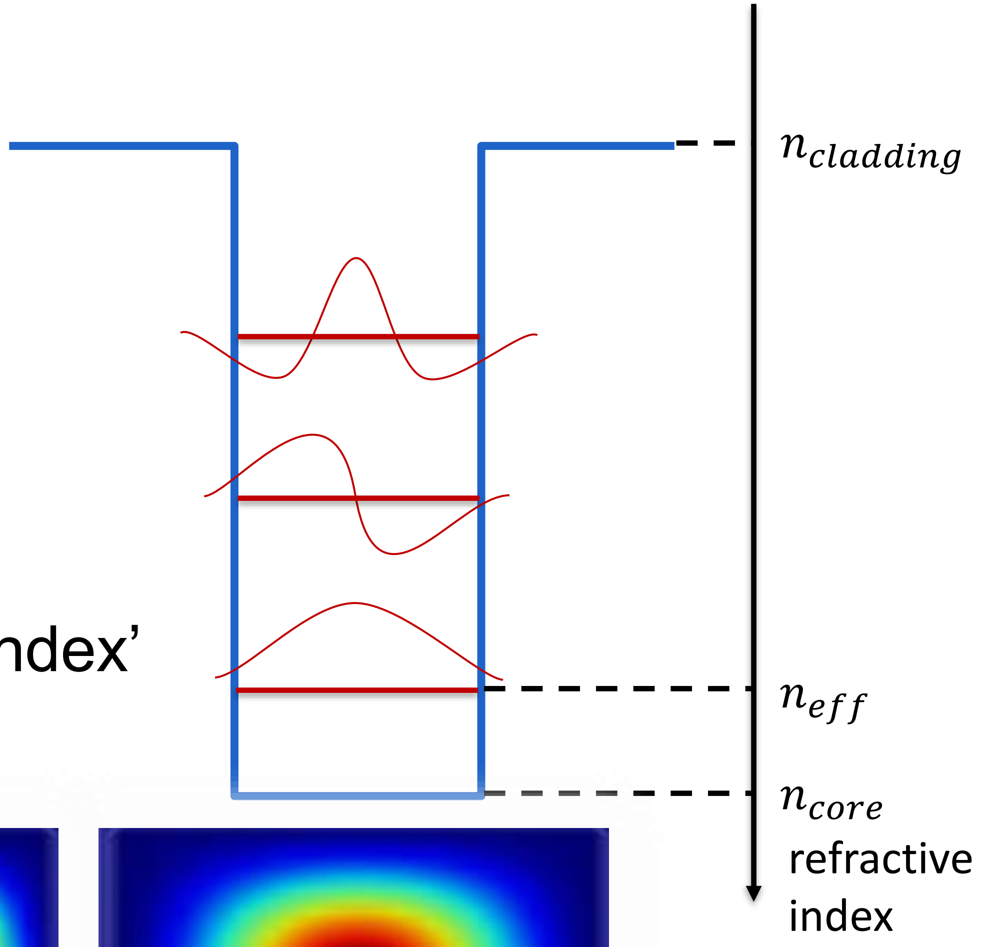
Solution of Maxwell's equation:

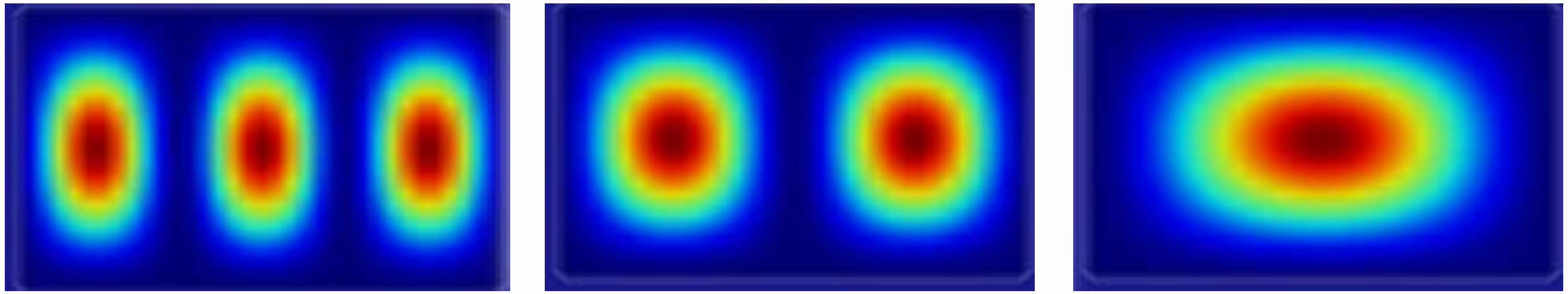
- Sine/cosine in the core
- Decaying exponential outside

There is an optical field outside the core!!!

Discrete mode(s) with 'effective refractive index'

- higher index contrast: more modes





WAVEGUIDE = POTENTIAL WELL FOR PHOTONS

Light prefers to reside in a material with high refractive index

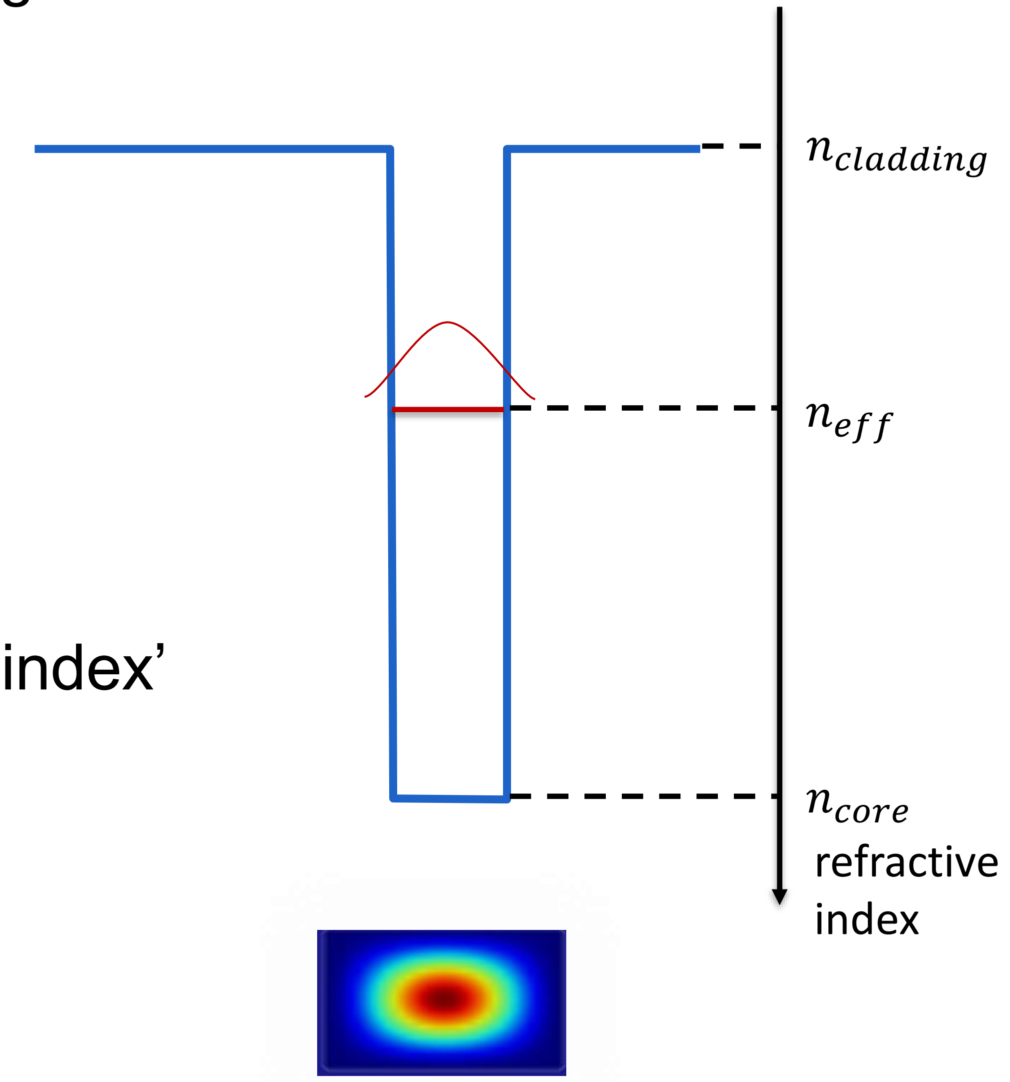
Solution of Maxwell's equation:

- Sine/cosine in the core
- Decaying exponential outside

There is an optical field outside the core!!!

Discrete mode(s) with 'effective refractive index'

- higher index contrast: more modes
- smaller waveguides: fewer modes

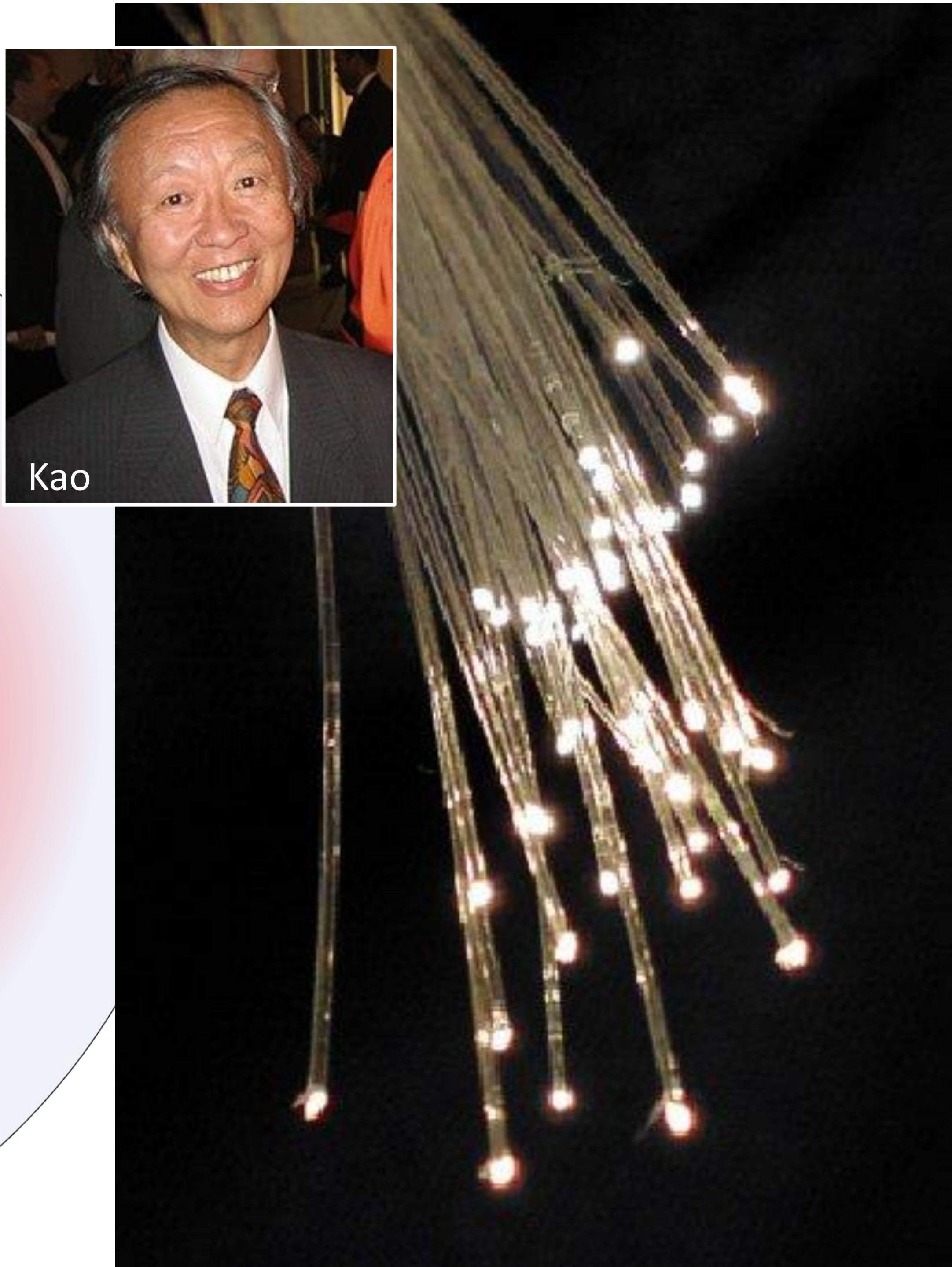


The optical fiber

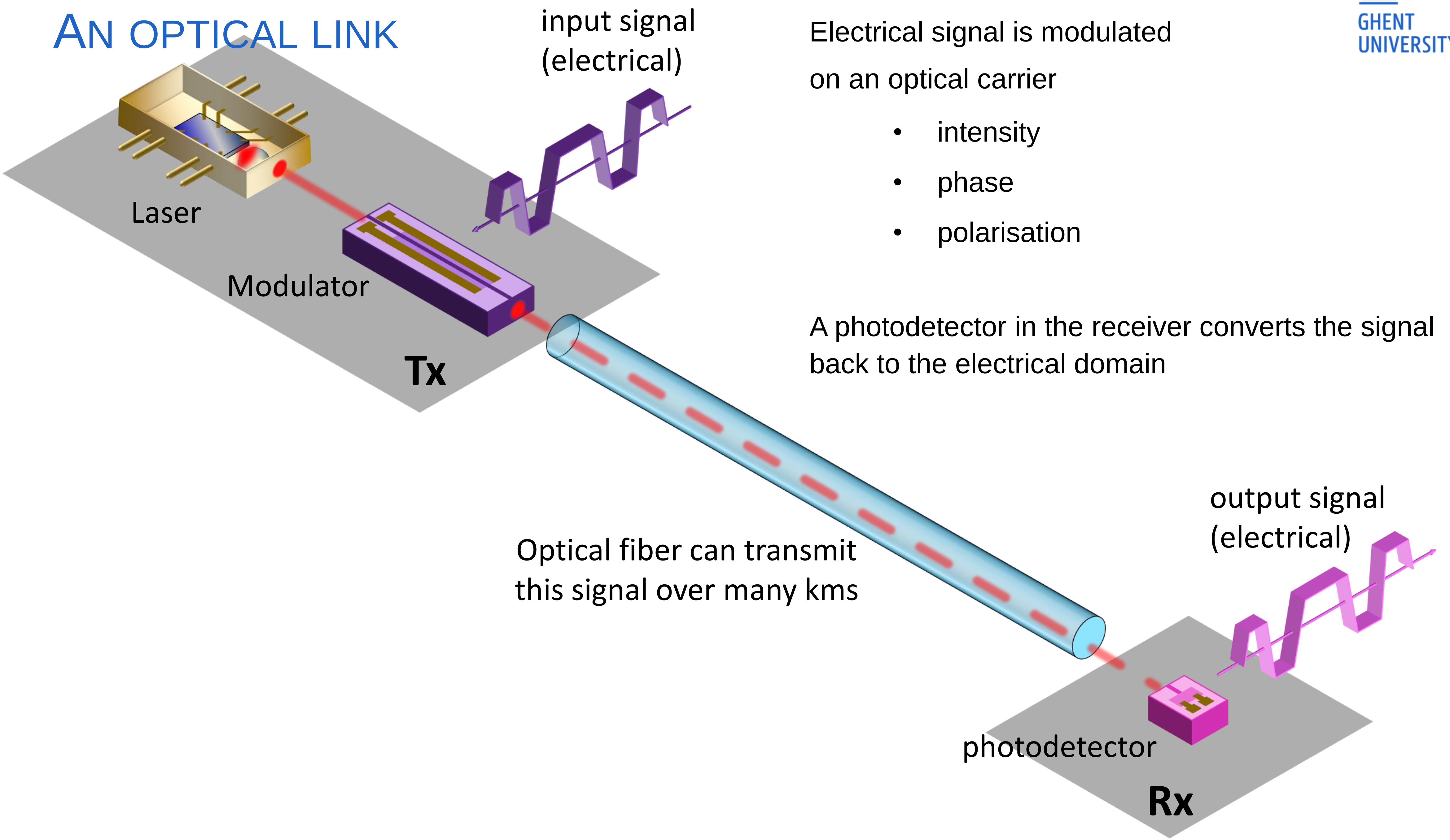
Making optical fibers out of very pure glass

- 9µm core
- 125µm cladding
- Very small index contrast

Attentuation < 1dB/km



AN OPTICAL LINK



Electrical signal is modulated on an optical carrier

- intensity
- phase
- polarisation

A photodetector in the receiver converts the signal back to the electrical domain

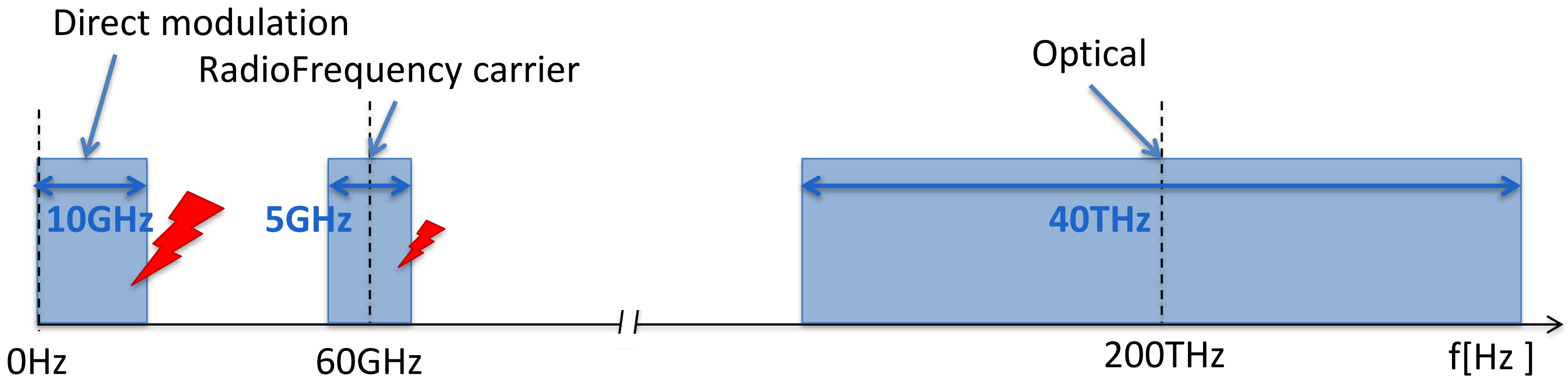
FIBERS OFFER "UNLIMITED" BANDWIDTH!

Maximum channel capacity C [bps] - (Shannon-Hartley theorem)

$$C = B \cdot \log_2\left(1 + \frac{S}{N}\right)$$

B = used bandwidth [Hz]

S/N = Signal to noise ratio



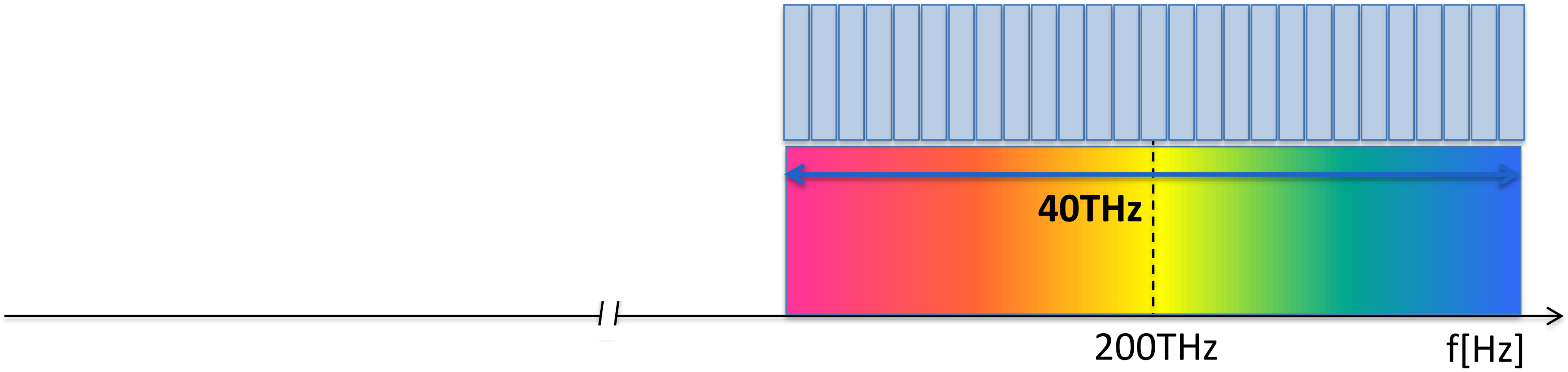
WAVELENGTH DIVISION MULTIPLEXING

Utilizing 40THz of bandwidth? [1200nm – 1650nm]

- No direct electrical modulation or detection

Solution: Wavelength Division multiplexing (WDM)

- Modulate on wavelength carriers



WDM Optical Link

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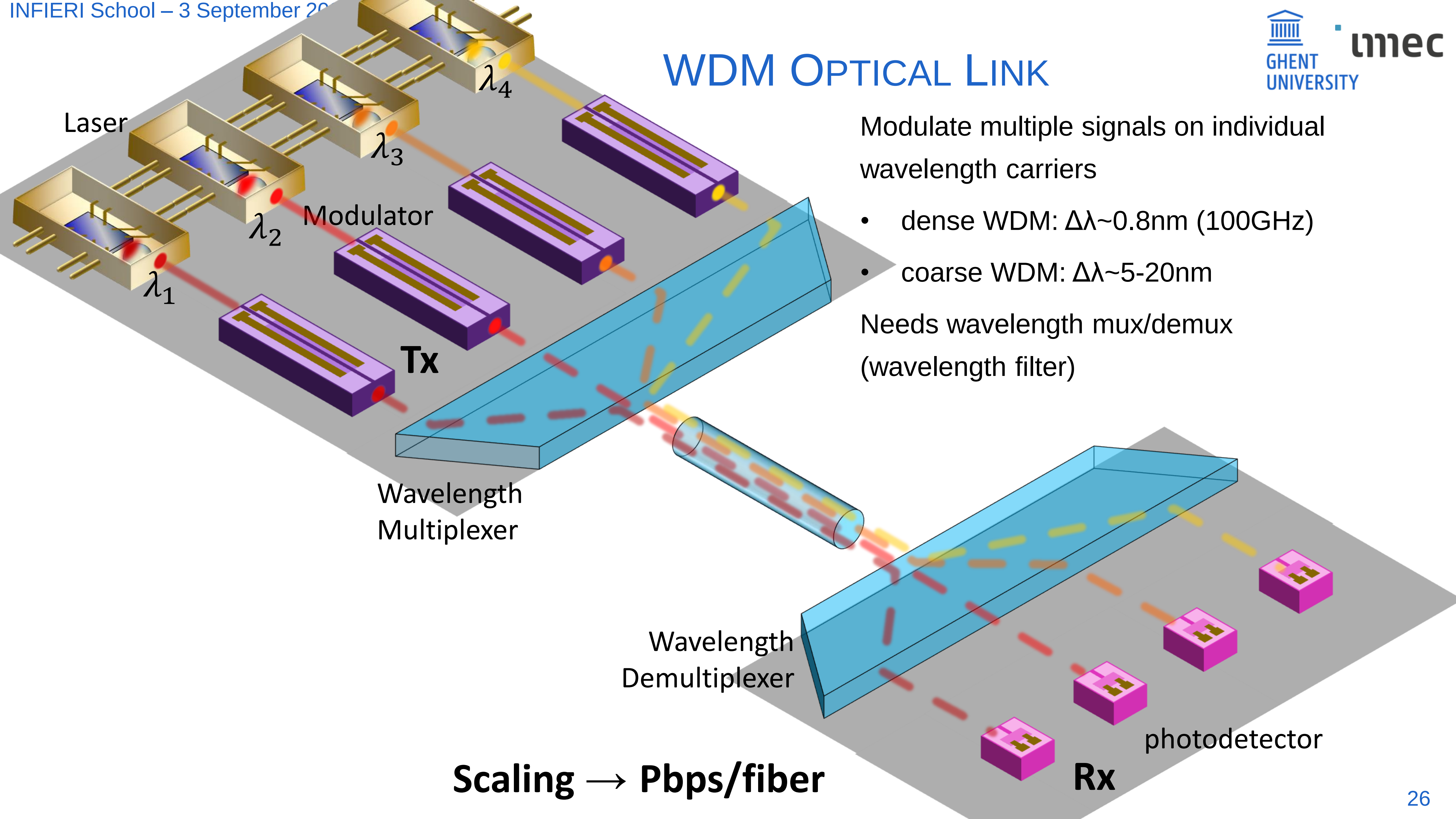
Modulate multiple signals on individual wavelength carriers

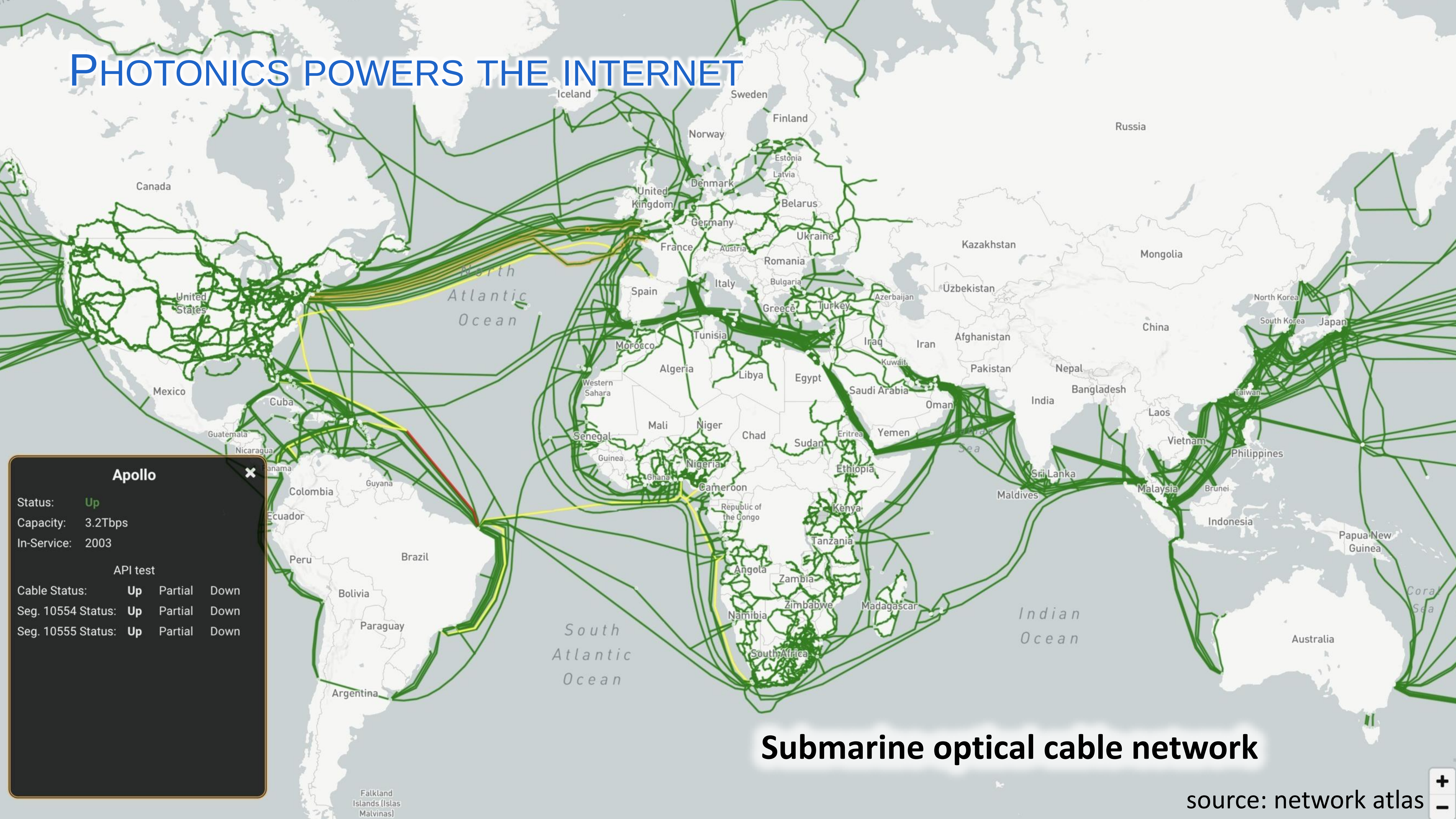
- dense WDM: Δλ~0.8nm (100GHz)
- coarse WDM: Δλ~5-20nm

Needs wavelength mux/demux (wavelength filter)



Scaling → Pbps/fiber

Photonics powers the internet



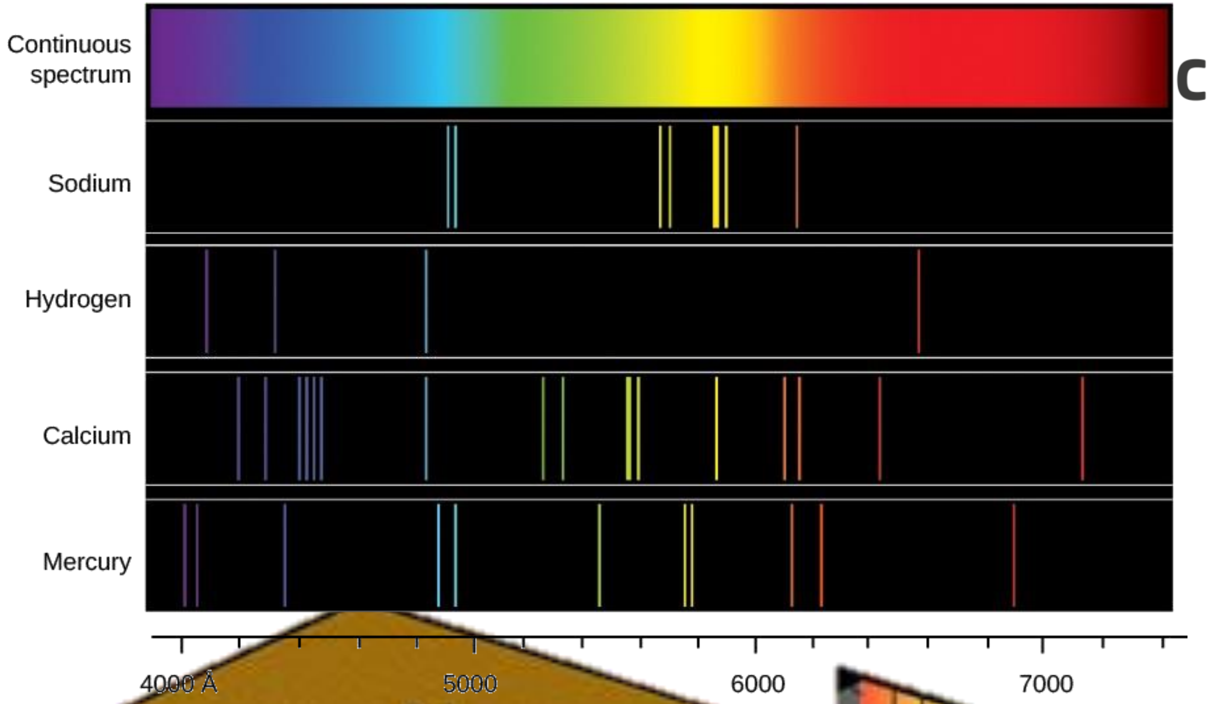
Submarine optical cable network

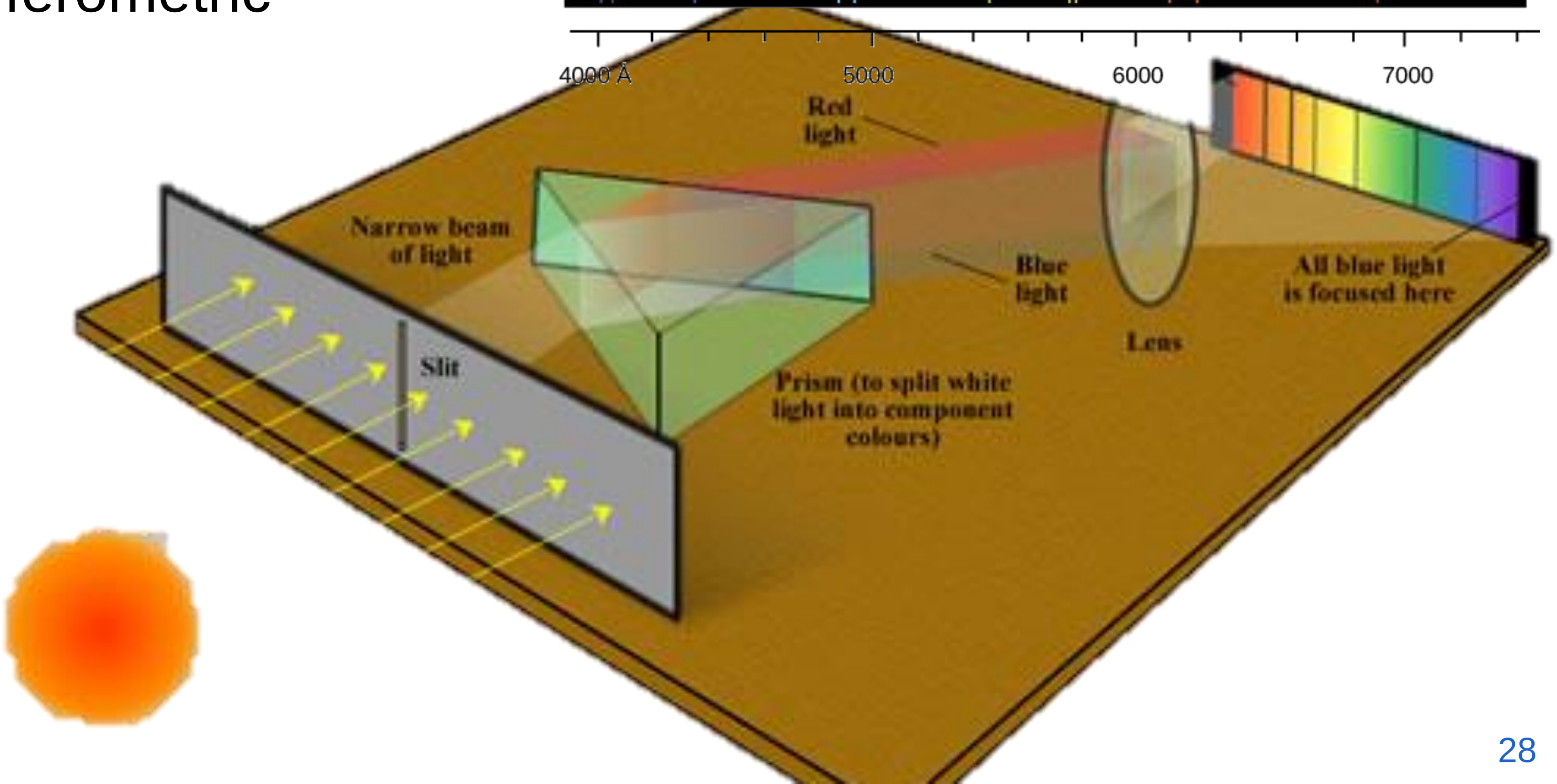
source: network atlas

PHOTONIC SENSING

Spectrometry / Spectroscopy

- separating/filtering the wavelengths in light
- Using dispersive or interferometric optical elements

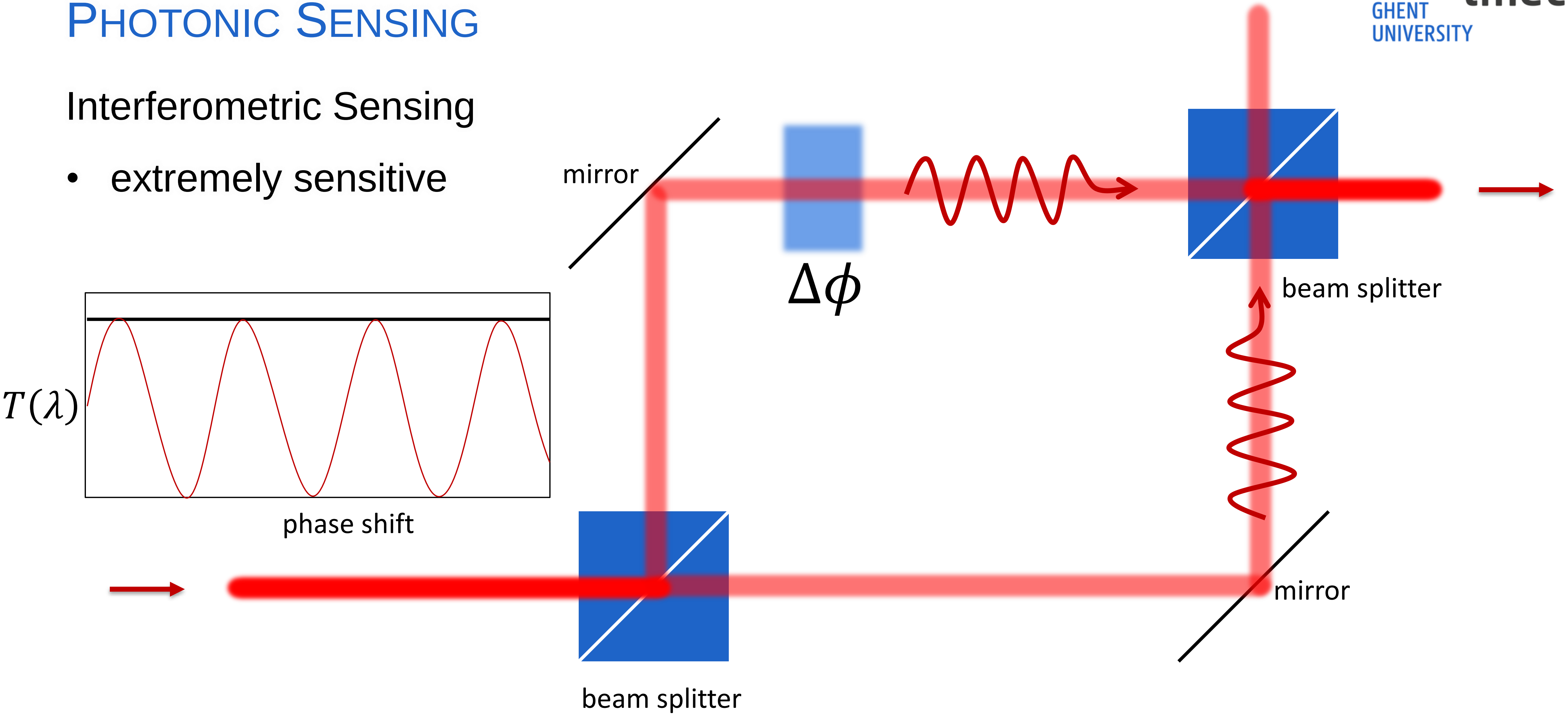




Photonic Sensing

Interferometric Sensing

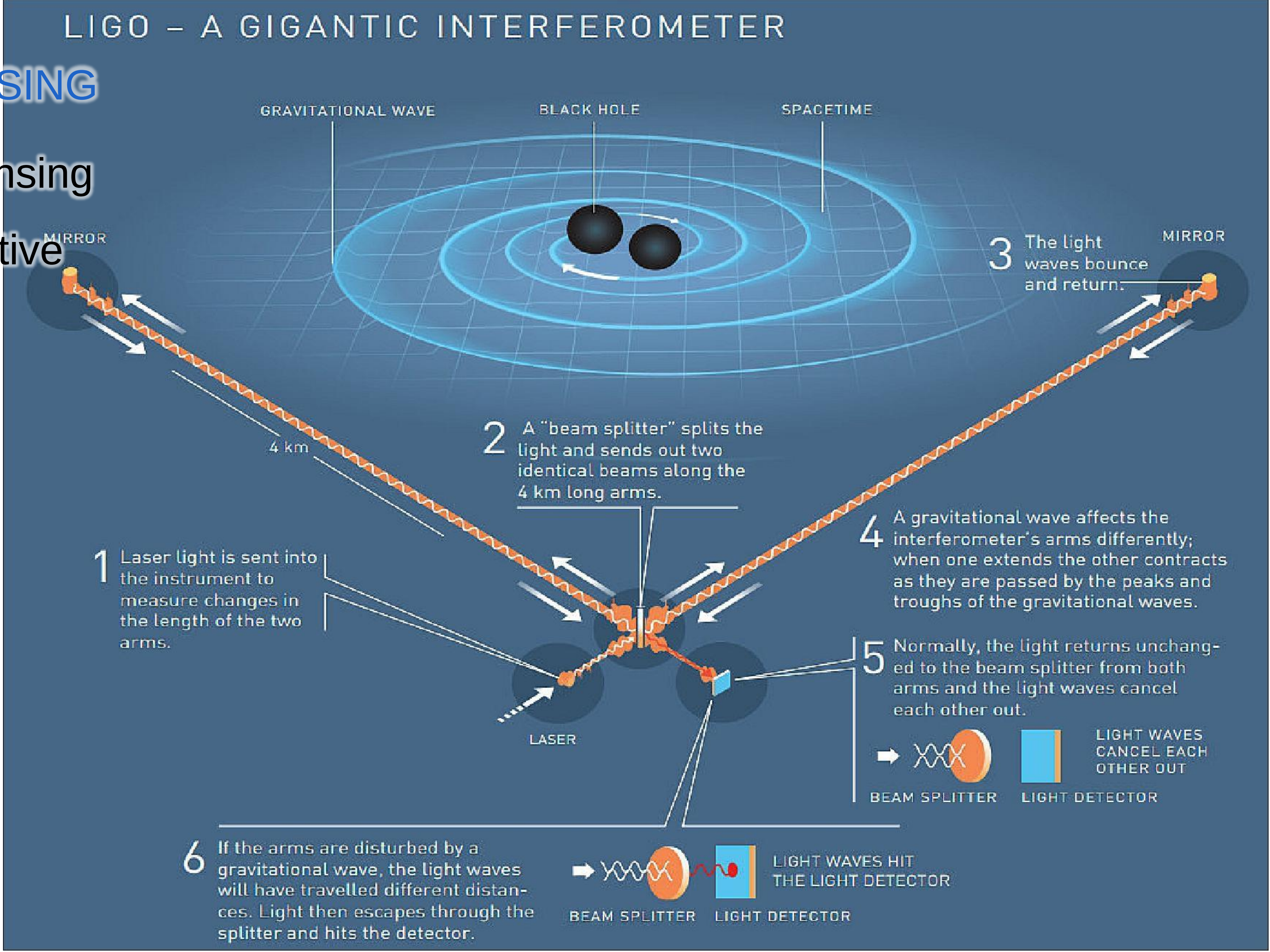
- extremely sensitive



Photonic Sensing

Interferometric Sensing

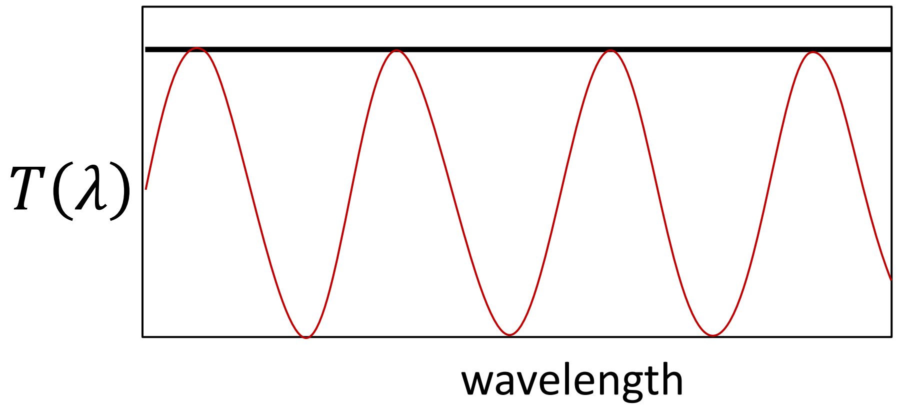
- extremely sensitive

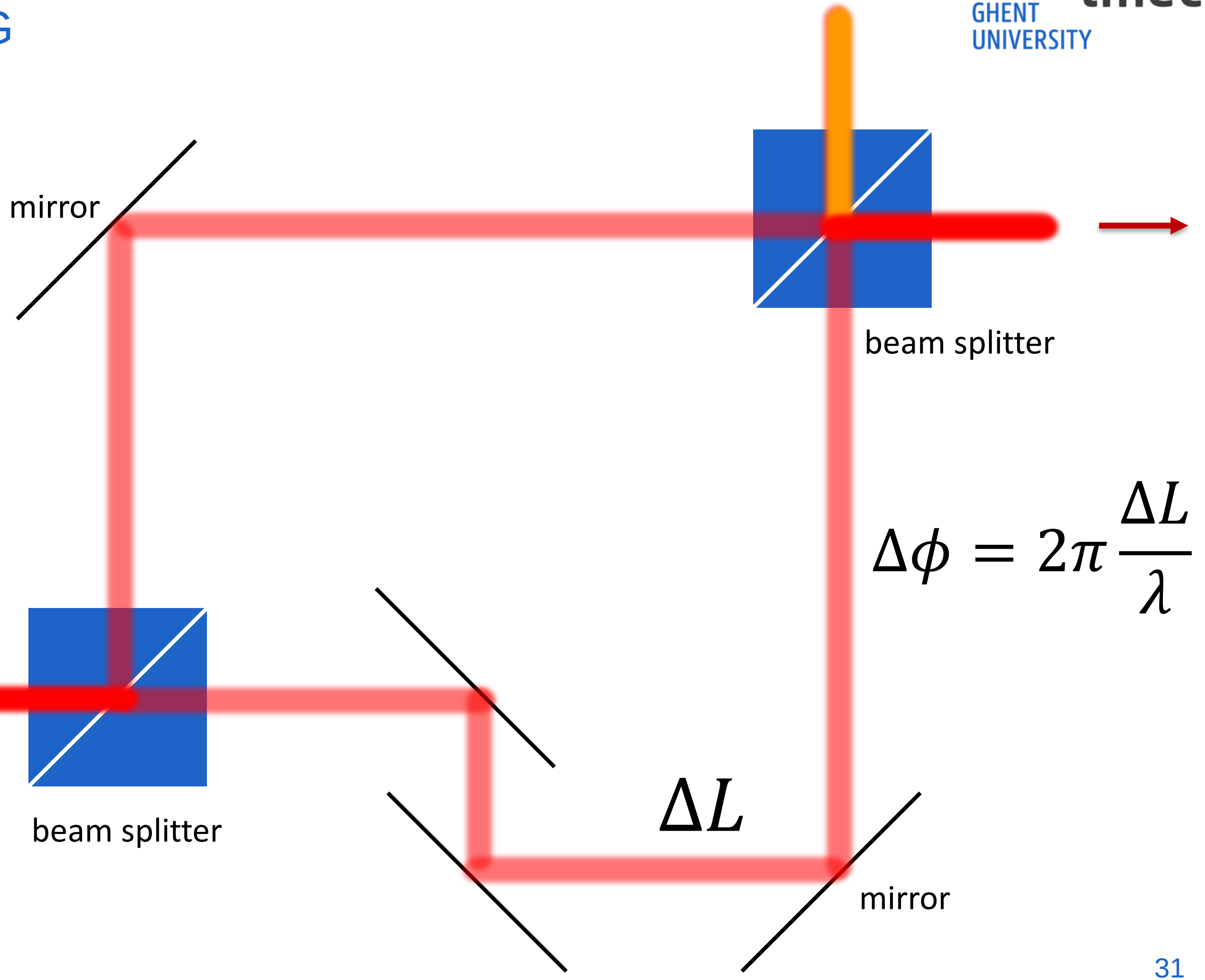


Wavelength Filtering

Interferometers with delays

- wavelength dependent



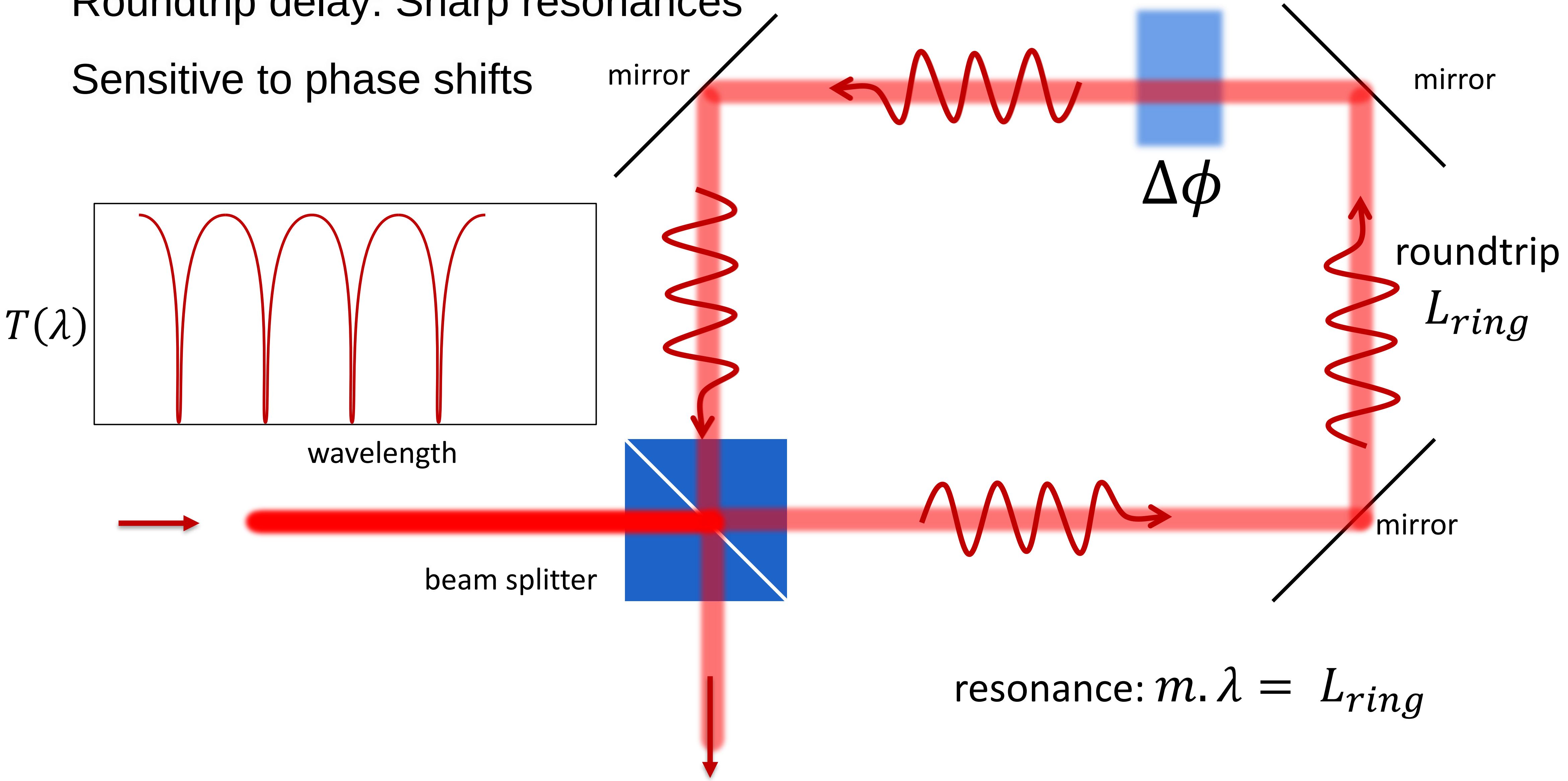


$$\Delta\phi = 2\pi\frac{\Delta L}{\lambda}$$

WAVELENGTH FILTERING: RESONATORS

Roundtrip delay: Sharp resonances

Sensitive to phase shifts

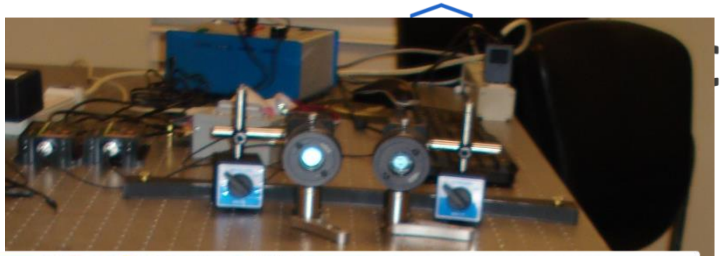


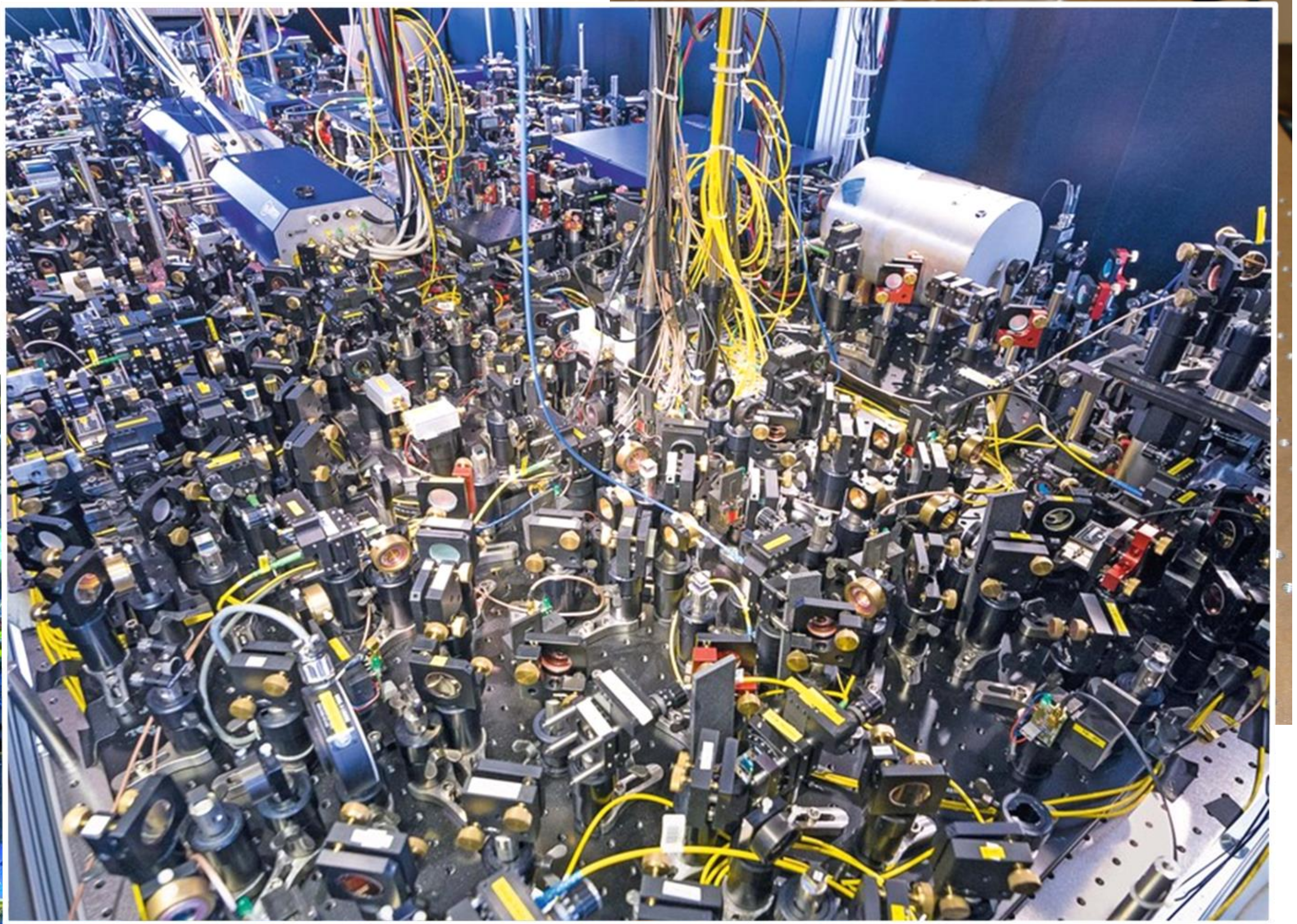
MANIPULATING BEAMS OF LIGHT

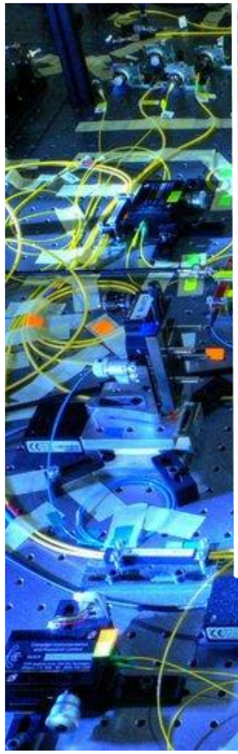
Using optical elements

- Lenses
- Mirrors
- Polarizers
- Shutters
- Spatial filters
- Wavelength filters
- Phase plates
- SLM

Does not scale very well







MANIPULATING LIGHT ON CHIPS

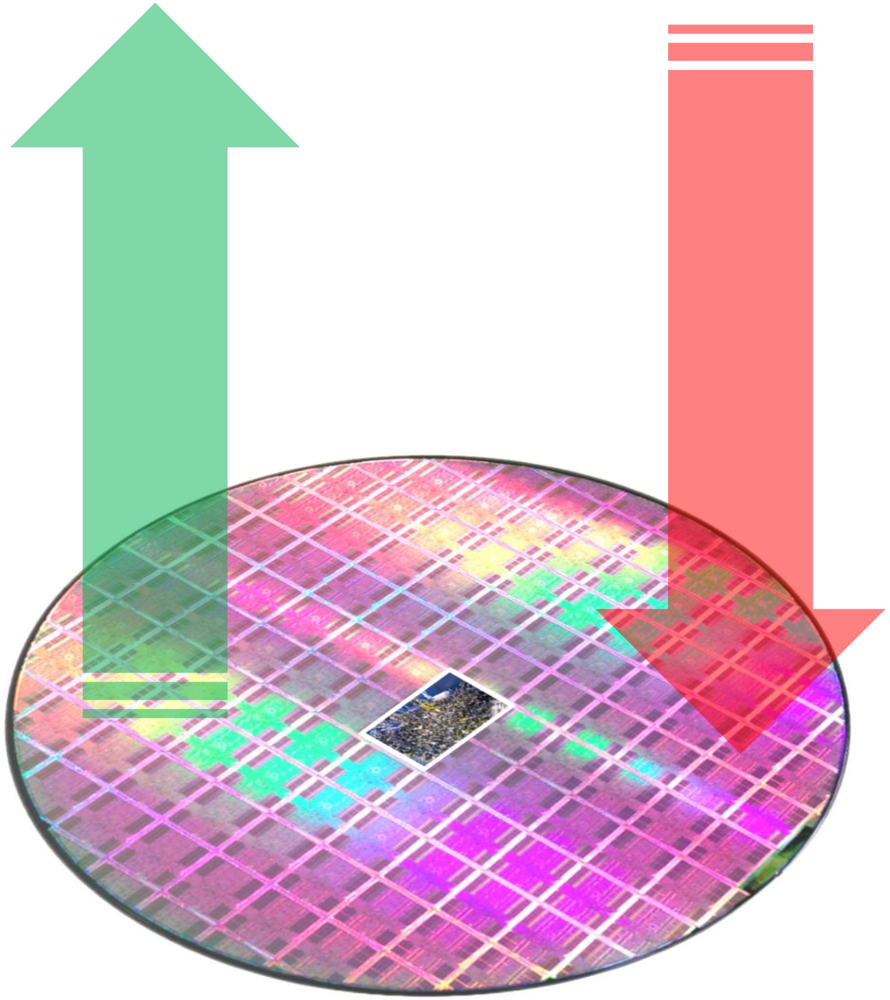
Complexity

Overall Performance

Reliability

Ergonomy

goes up



Power consumption

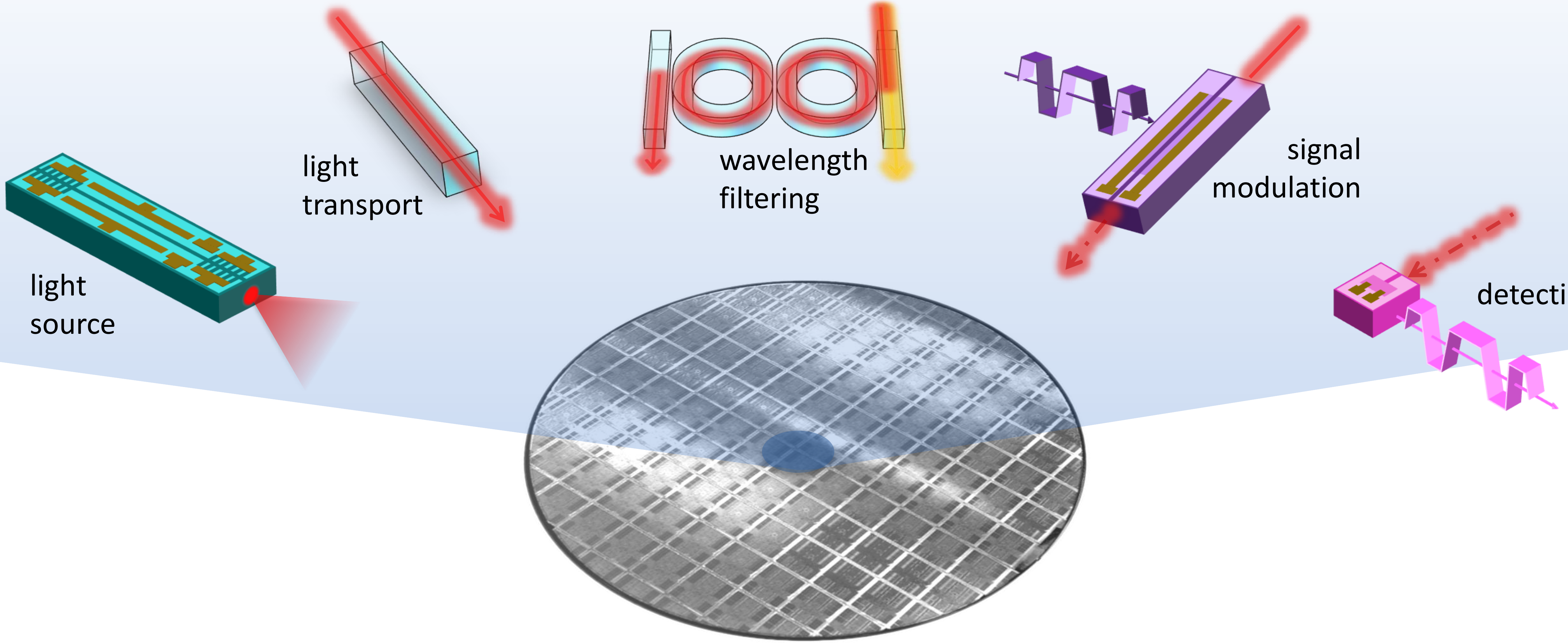
Ecological Footprint

Cost

goes down

The benefits of scale

Photonic Integration: many functions on a chip

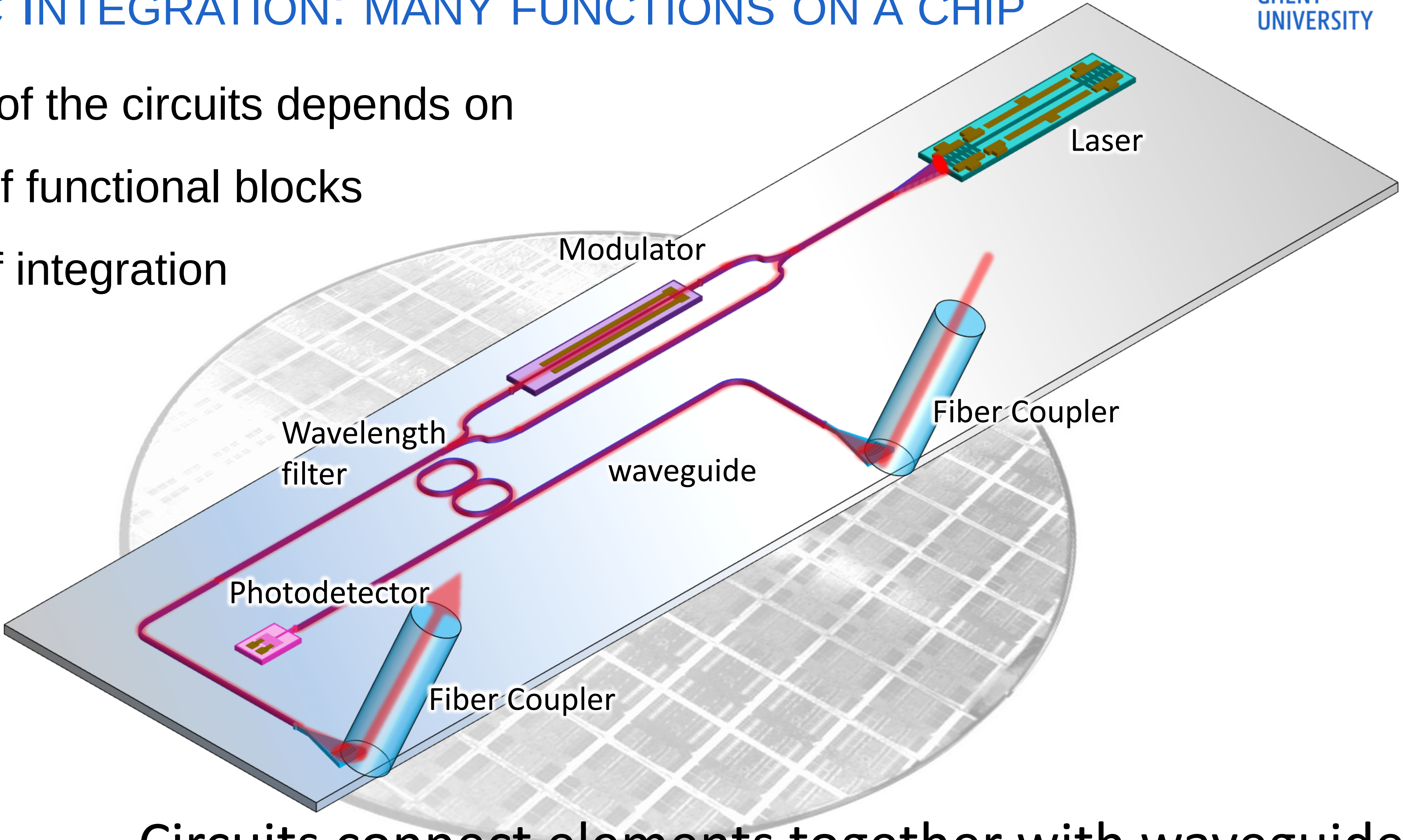


Circuits connect elements together with waveguides

PHOTONIC INTEGRATION: MANY FUNCTIONS ON A CHIP

Complexity of the circuits depends on

- number of functional blocks
- density of integration



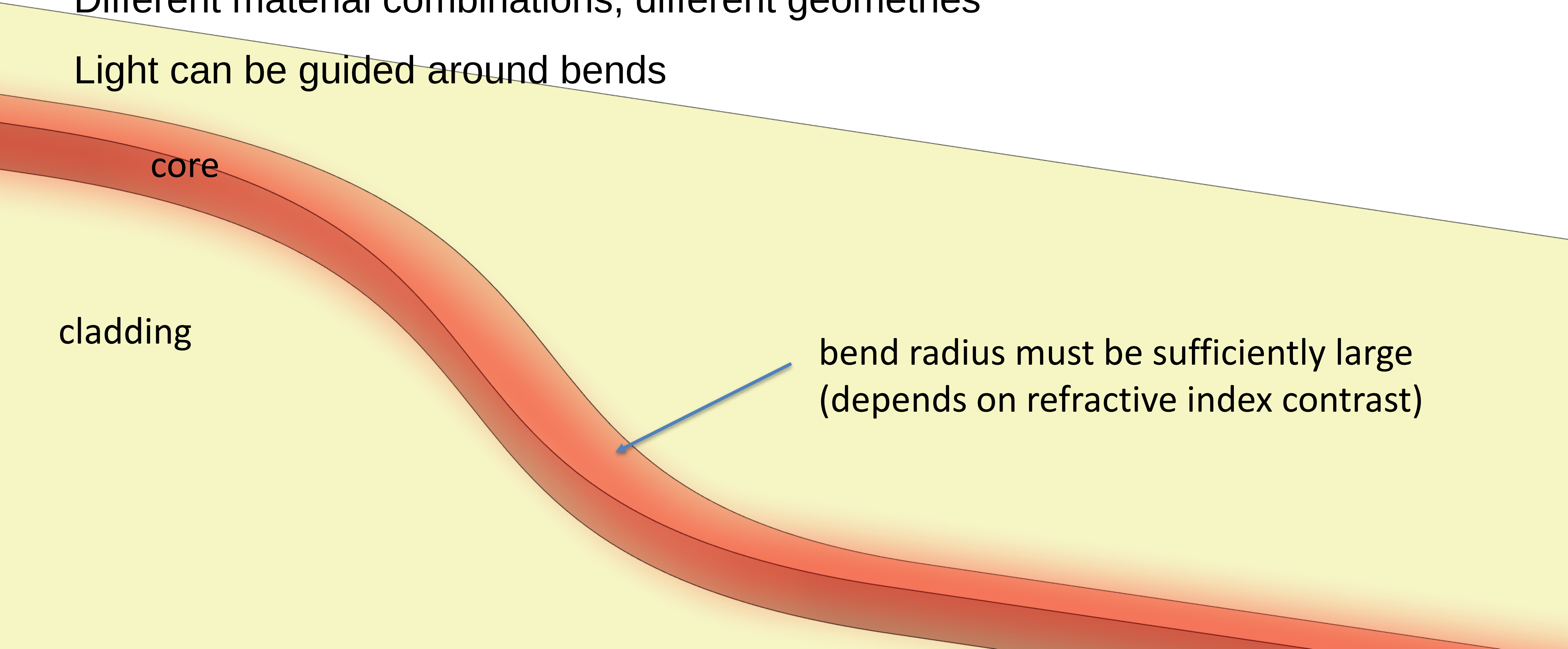
Circuits connect elements together with waveguides

WAVEGUIDE : (RECTANGULAR) LINE ON A SUBSTRATE

High index core surrounded by low-index cladding

Different material combinations, different geometries

Light can be guided around bends

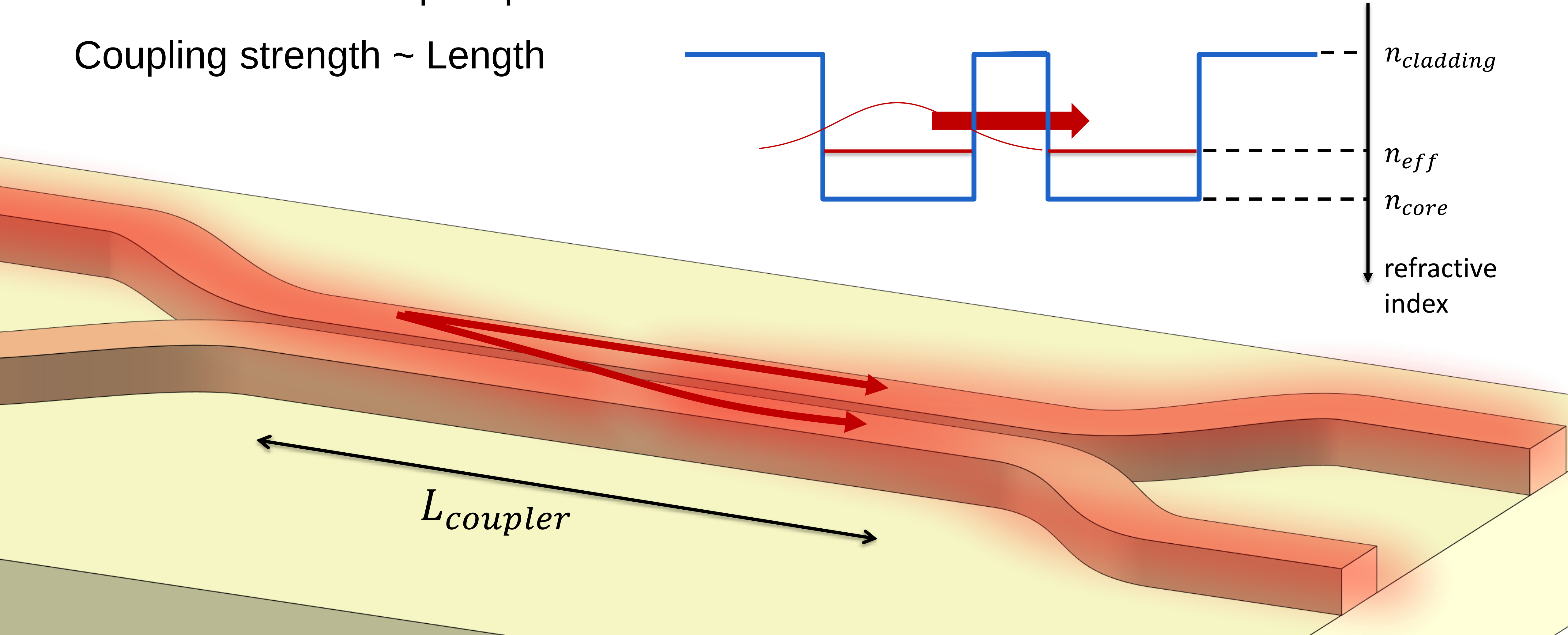


Directional Coupler = Beam Splitter

Two waveguides close together: light can couple

= similar as two coupled potential wells

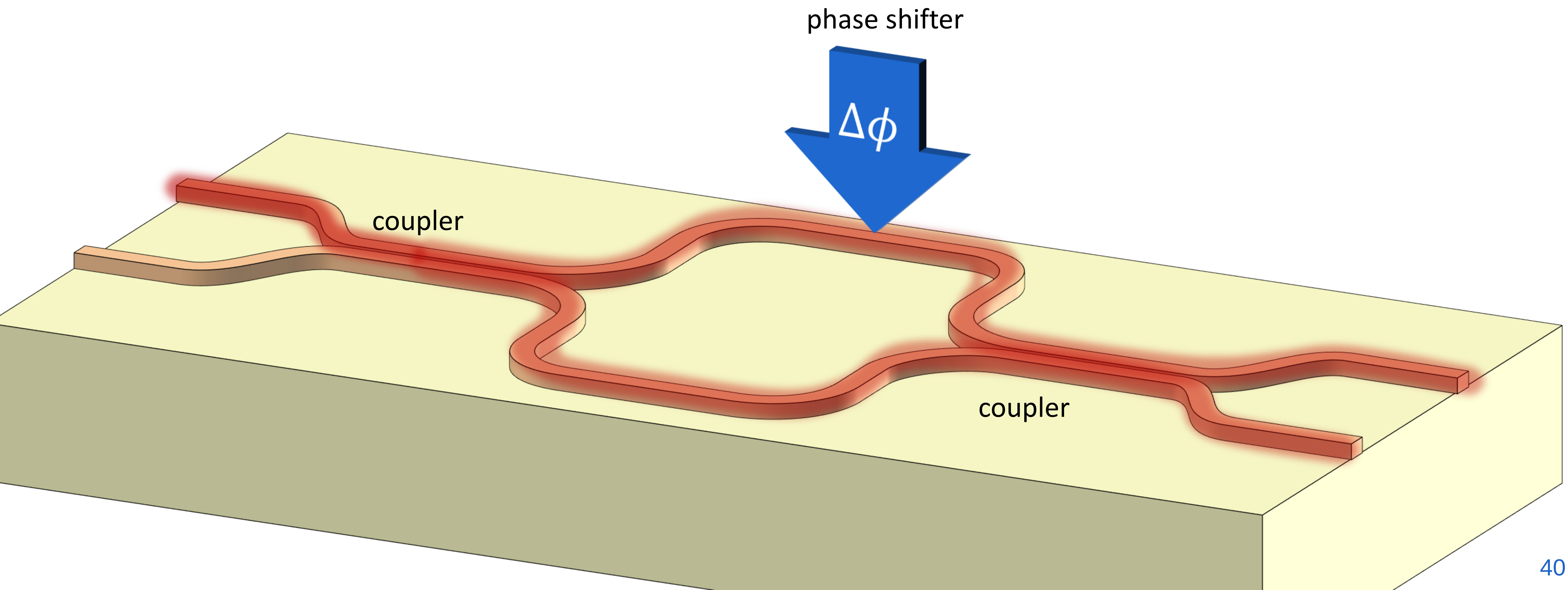
Coupling strength ~ Length



MZI: TRANSLATED TO A CHIP

beam splitters + waveguides

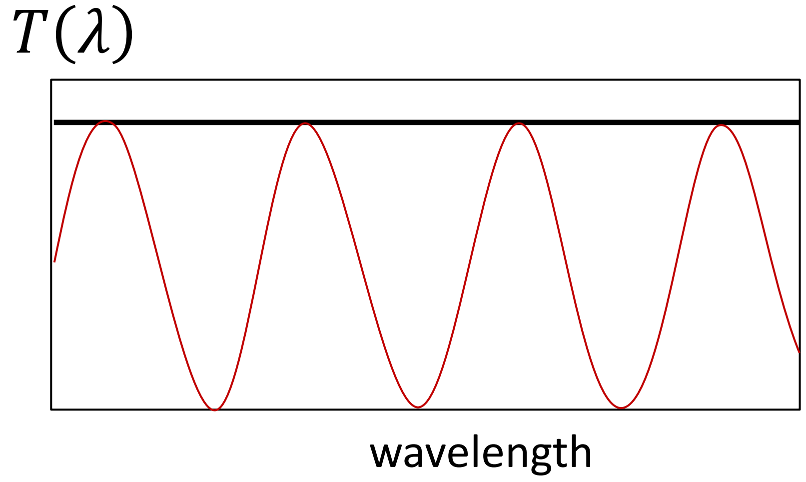
Active phase shifter in one arm: switching or modulating of the output



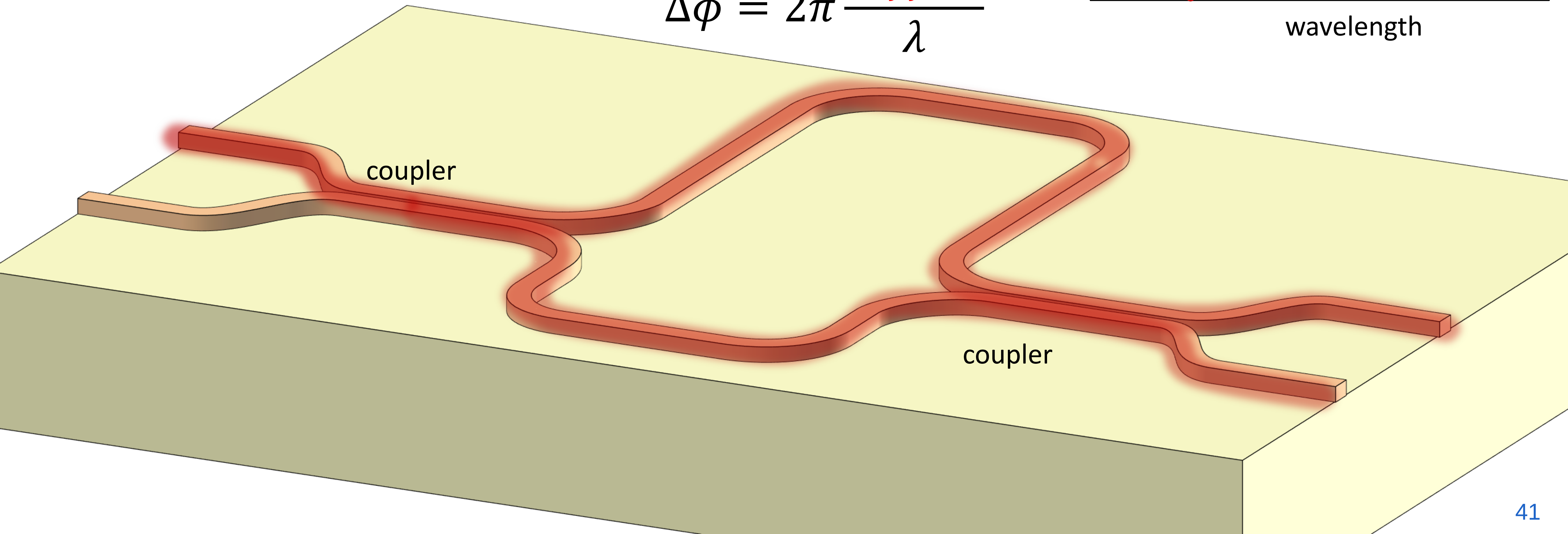
MZI: TRANSLATED TO A CHIP

beam splitters + waveguides

delay line will give a wavelength dependent response



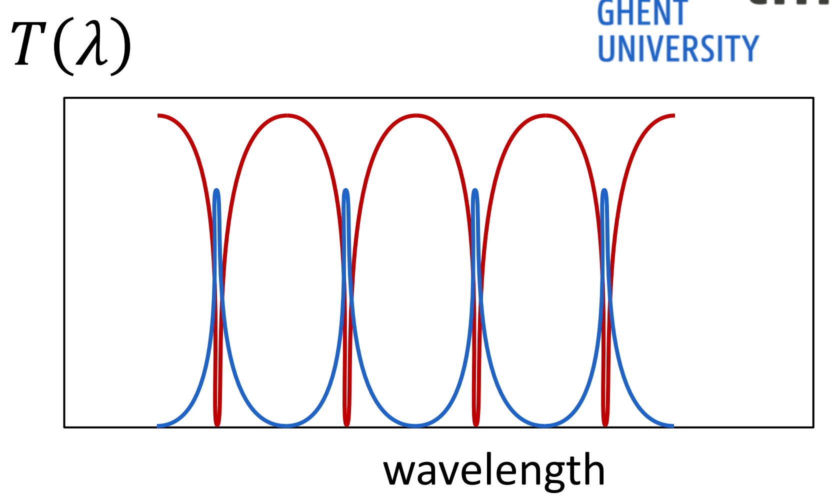
$$\Delta\phi = 2\pi \frac{n_{eff}\Delta L}{\lambda}$$

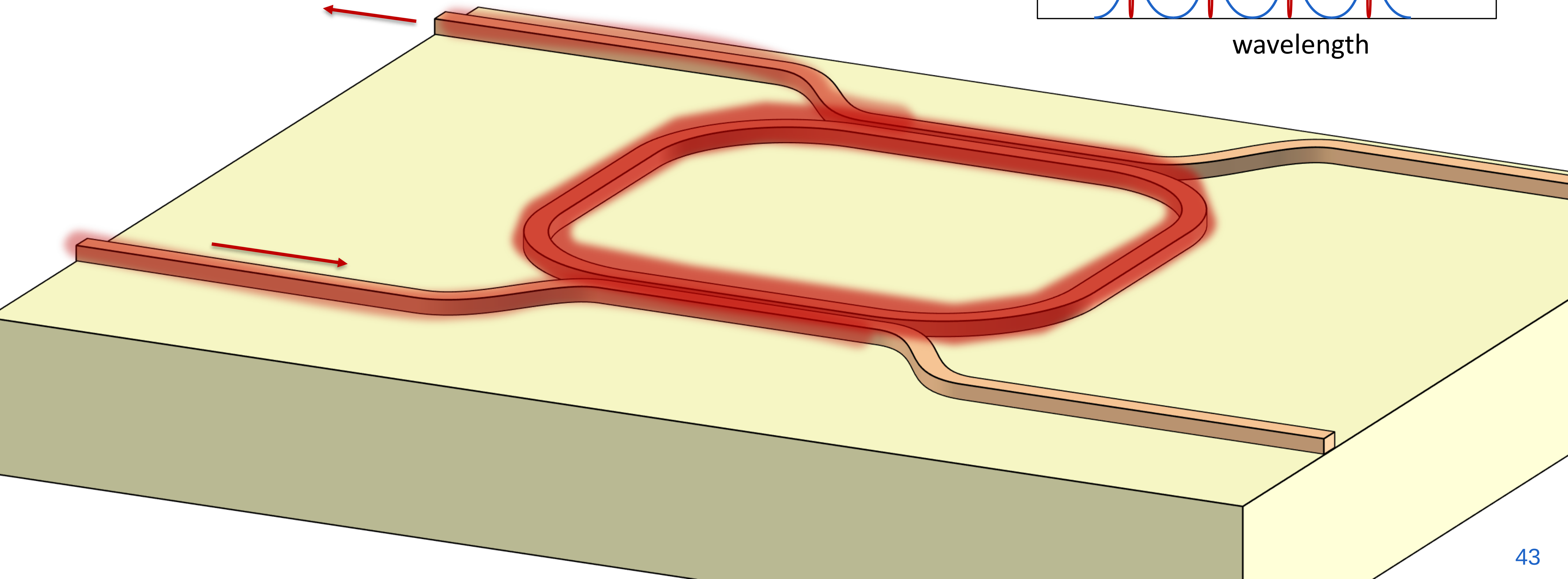


Ring Resonators

Optical feedback loop

Resonance when $n_{eff} L_{ring} = m.\lambda$

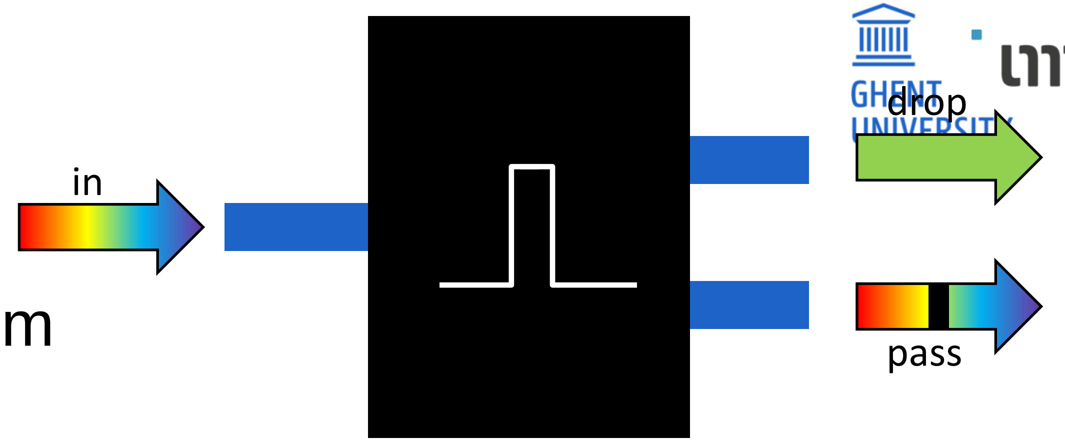




WAVELENGTH FILTERING

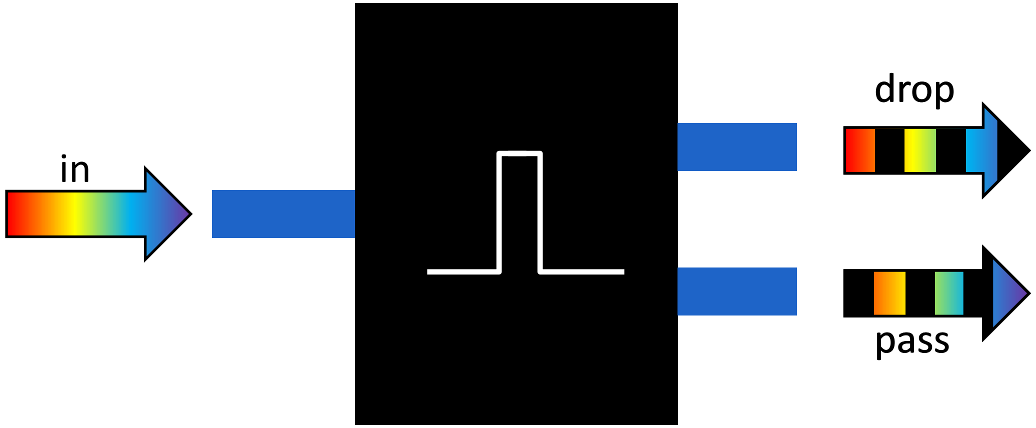
channel drop filter

- selects a passband from a wavelength range



interleaver

- separates alternating wavelength bands



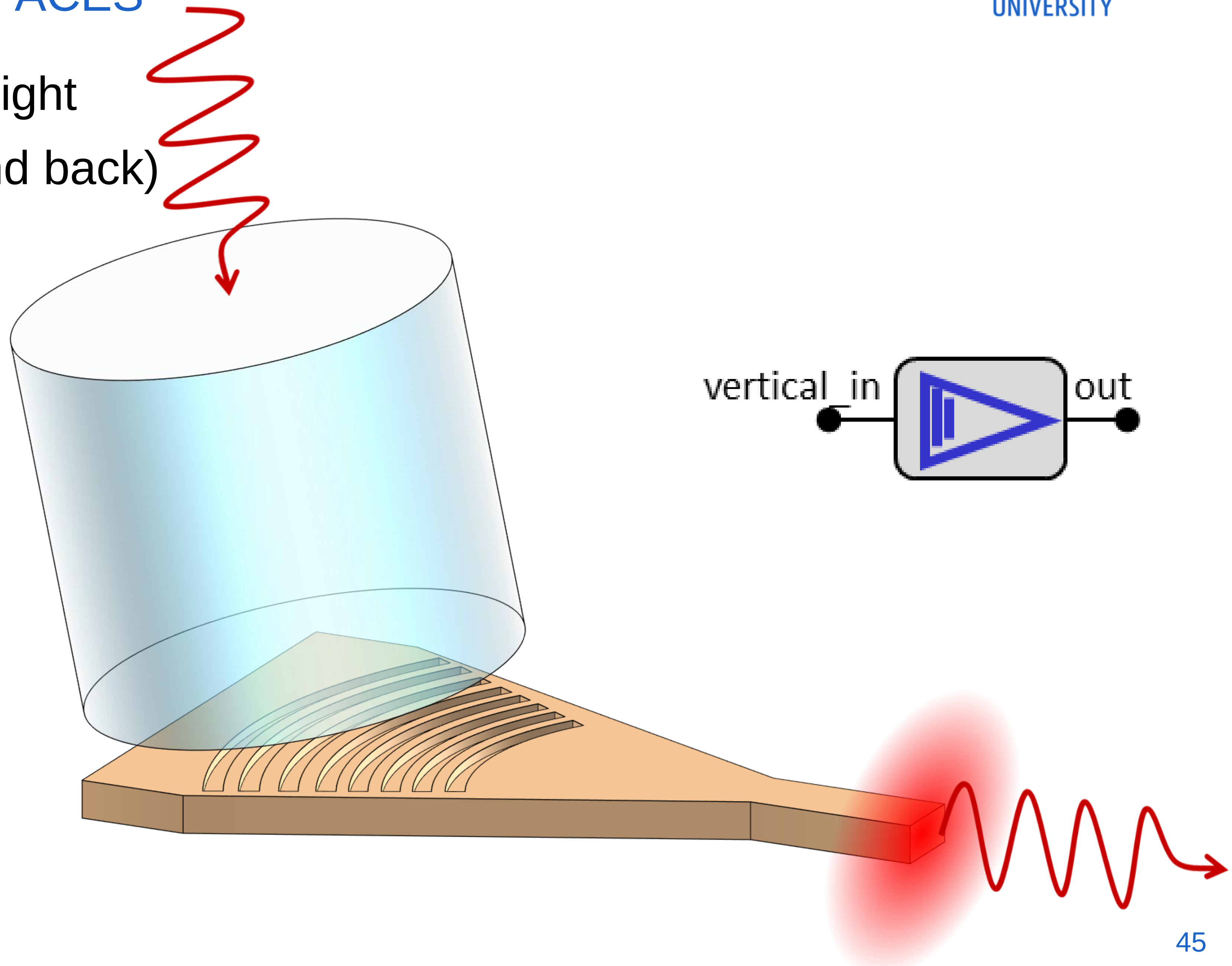
demultiplexer

- separates multiple wavelength channels

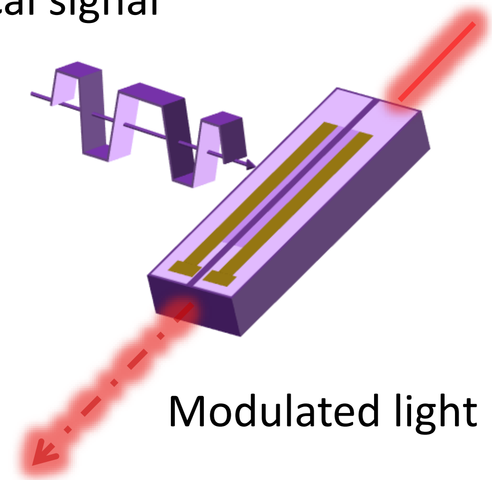
VERTICAL FIBER INTERFACES

Diffraction grating couples light from fiber to waveguide (and back)

- wavelength dependent



ELECTRICAL MODULATION



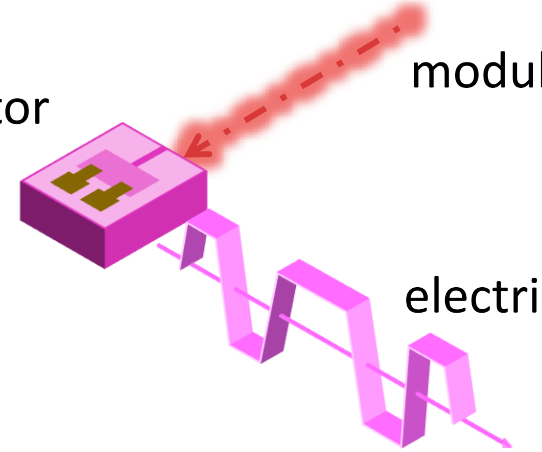
Electrical actuation: Switching and modulation

- Thermal
- Carrier injection/extraction
- Electro-optics

Different applications:

- Tuning: slow, analog
- Switching: slow, digital (<kHz), full amplitude
- Signal modulation: fast (GHz – 100GHz)
  - amplitude
  - phase

PHOTODETECTION



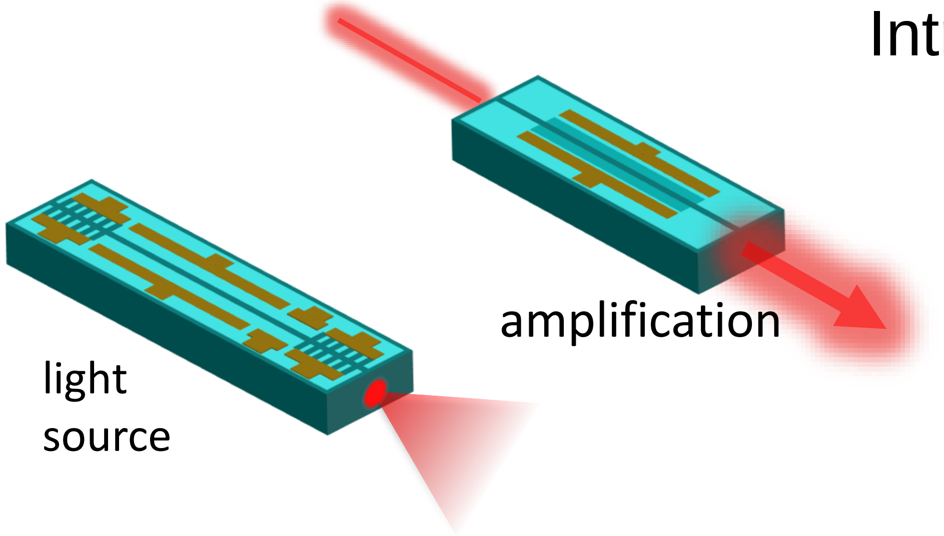
Mechanisms

- **photodiodes**: absorbed photon creates electron-hole pair.
  - p-i-n diode
  - metal-semiconductor-metal diode
- **photoconductors**: absorbed photon creates free carriers
- **photobolometers**: absorbed photon heats material, which then changes electrical resistivity

Examples

- III-V semiconductors (visible, telecom, MIR)
- Germanium (telecom)
- Silicon (visible, NIR)

LASERS AND AMPLIFIERS



Introducing optical gain on a PIC

- semiconductors (III-V, Germanium) can be electrically pumped
- rare-earth (Erbium) can be incorporated in glass waveguides
- parametric gain (four wave mixing) requires nonlinear material

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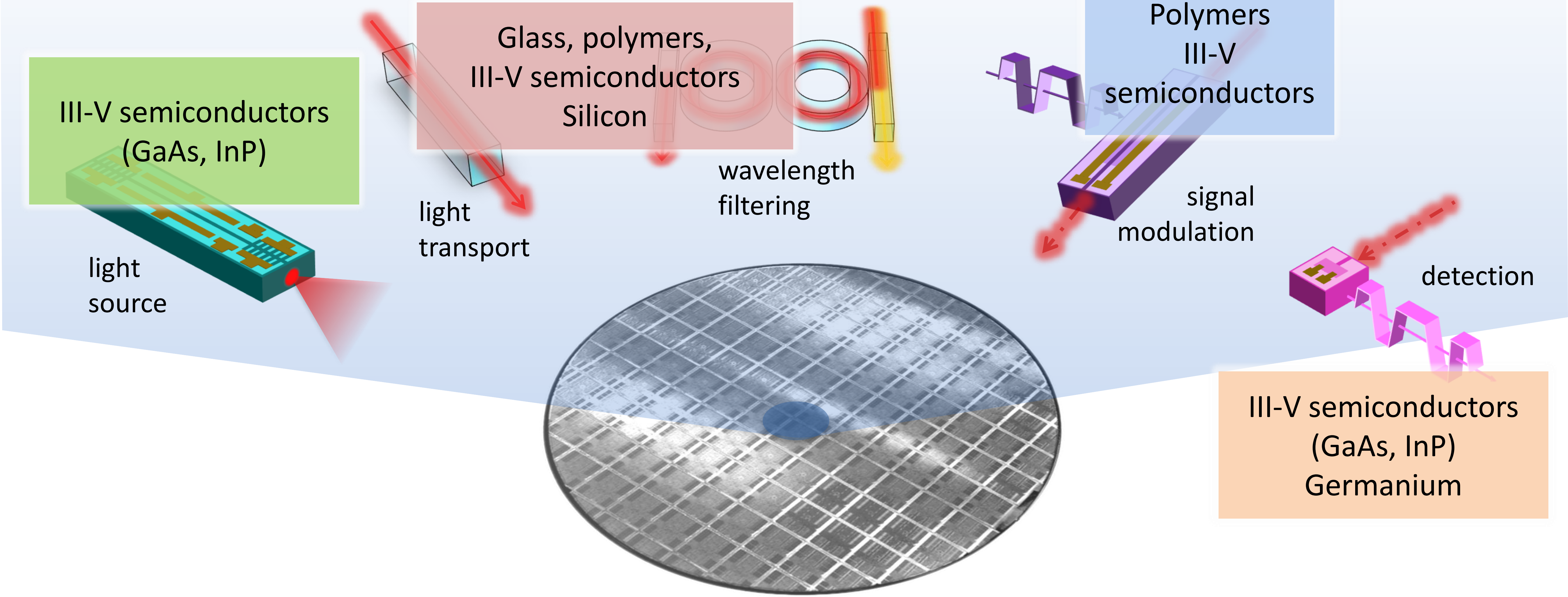
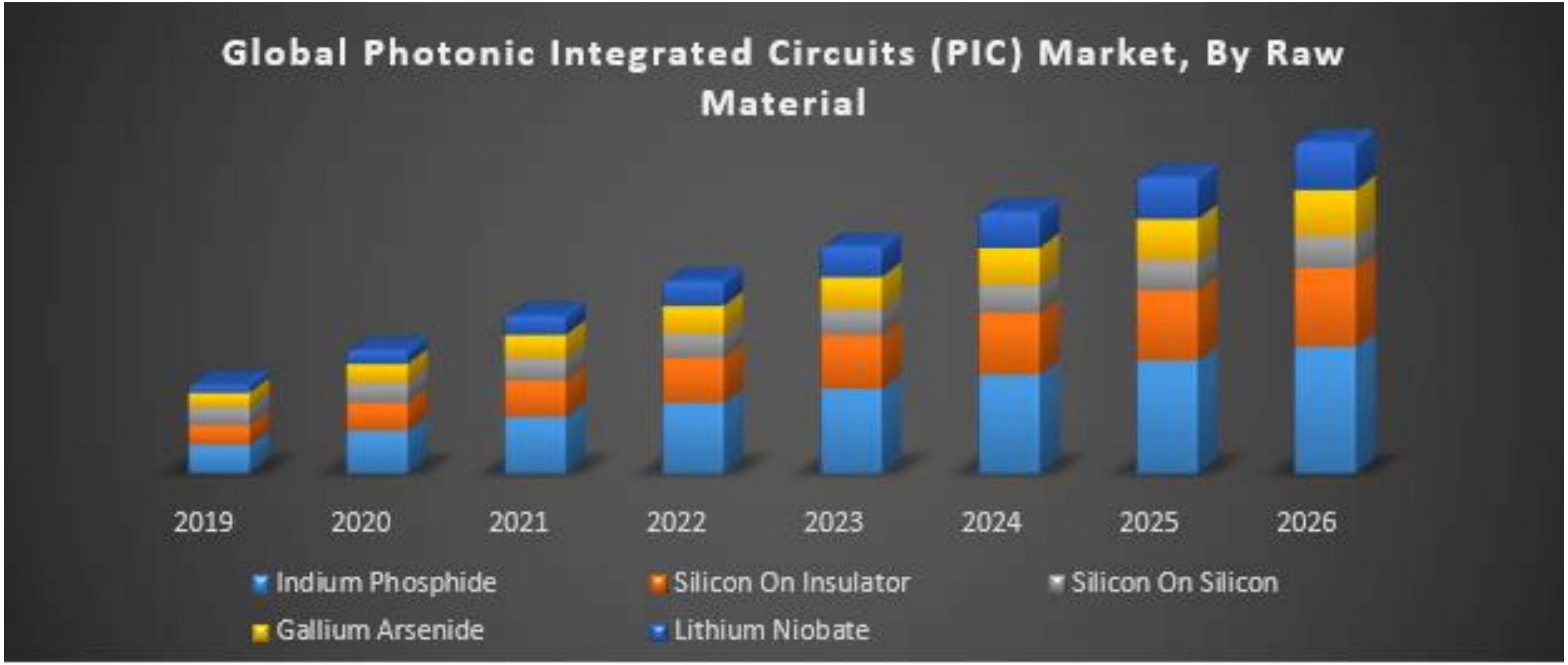
PHOTONIC INTEGRATION: A MIX OF MATERIALS



GROWING PHOTONIC CHIP MARKET

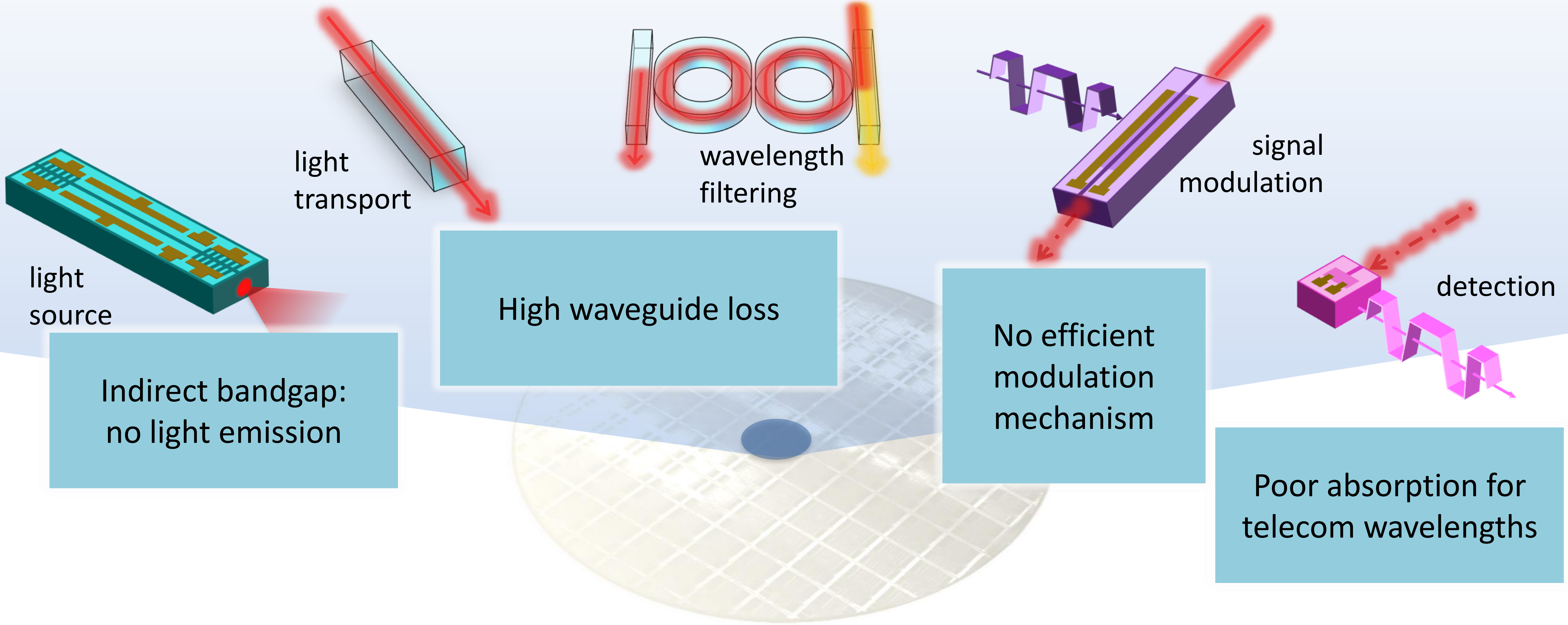
Different material systems



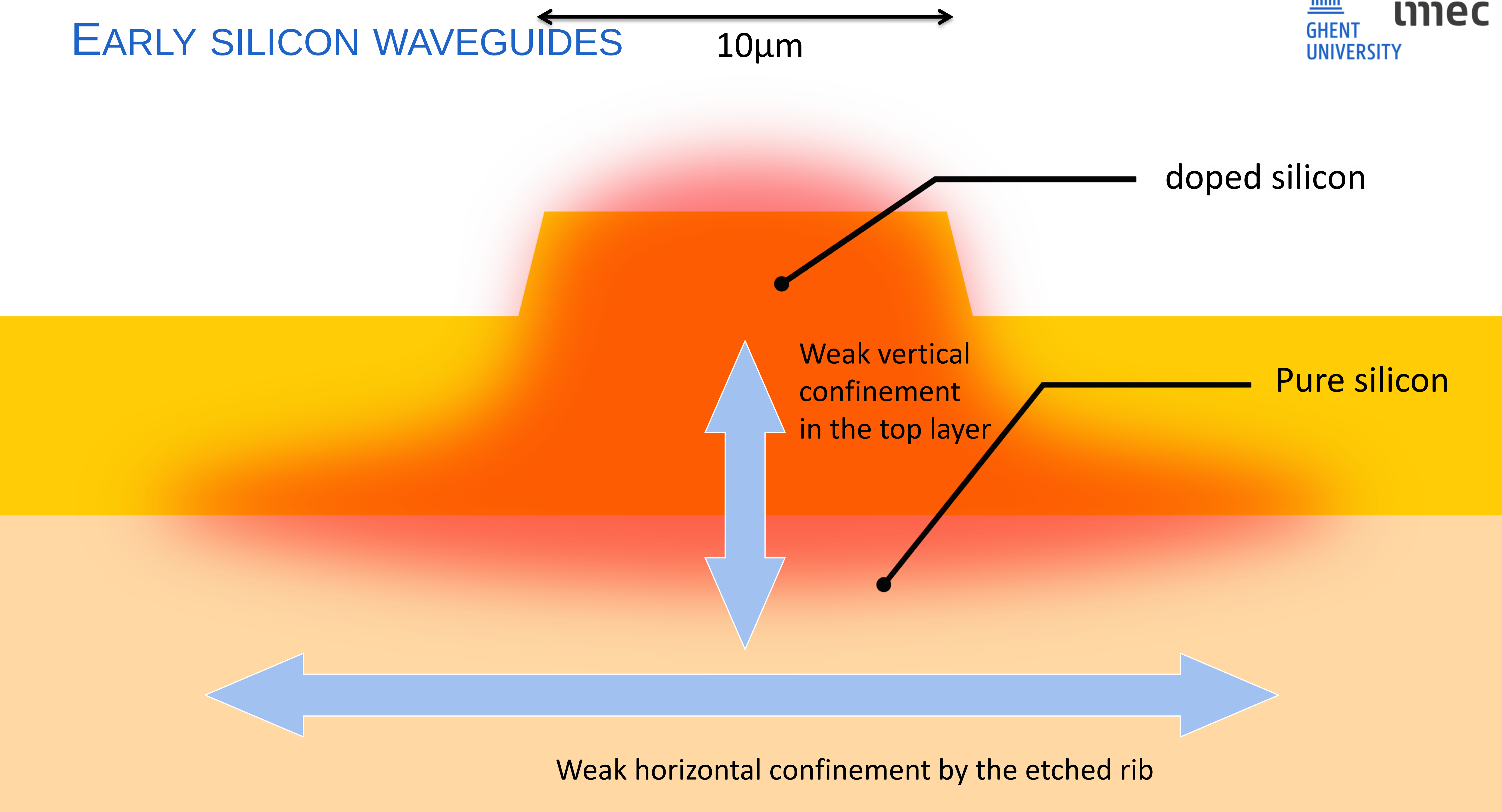
75% = semiconductor technology

source: maximizemarketresearch

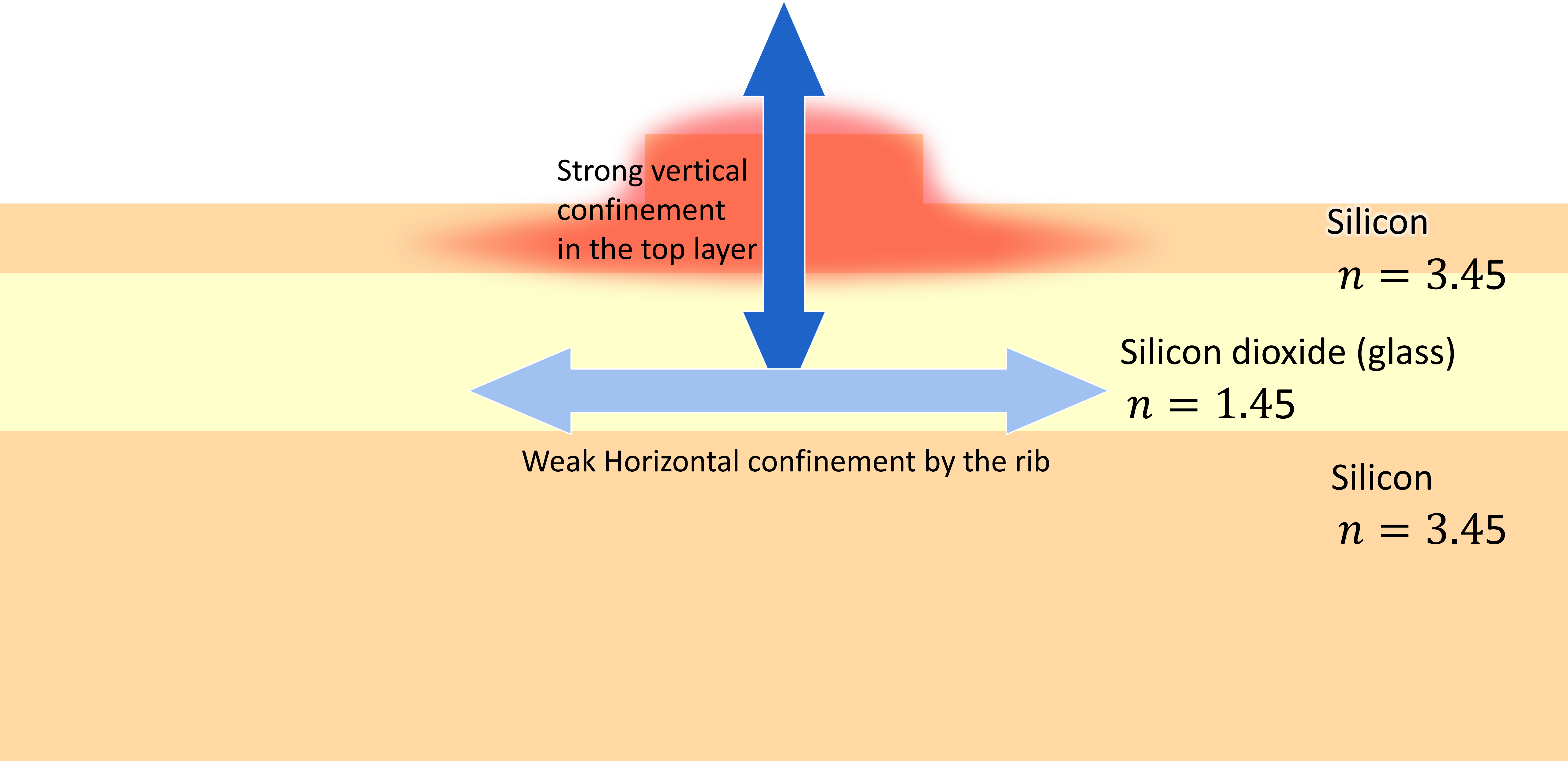
SILICON IS NOT A GOOD PHOTONIC MATERIAL



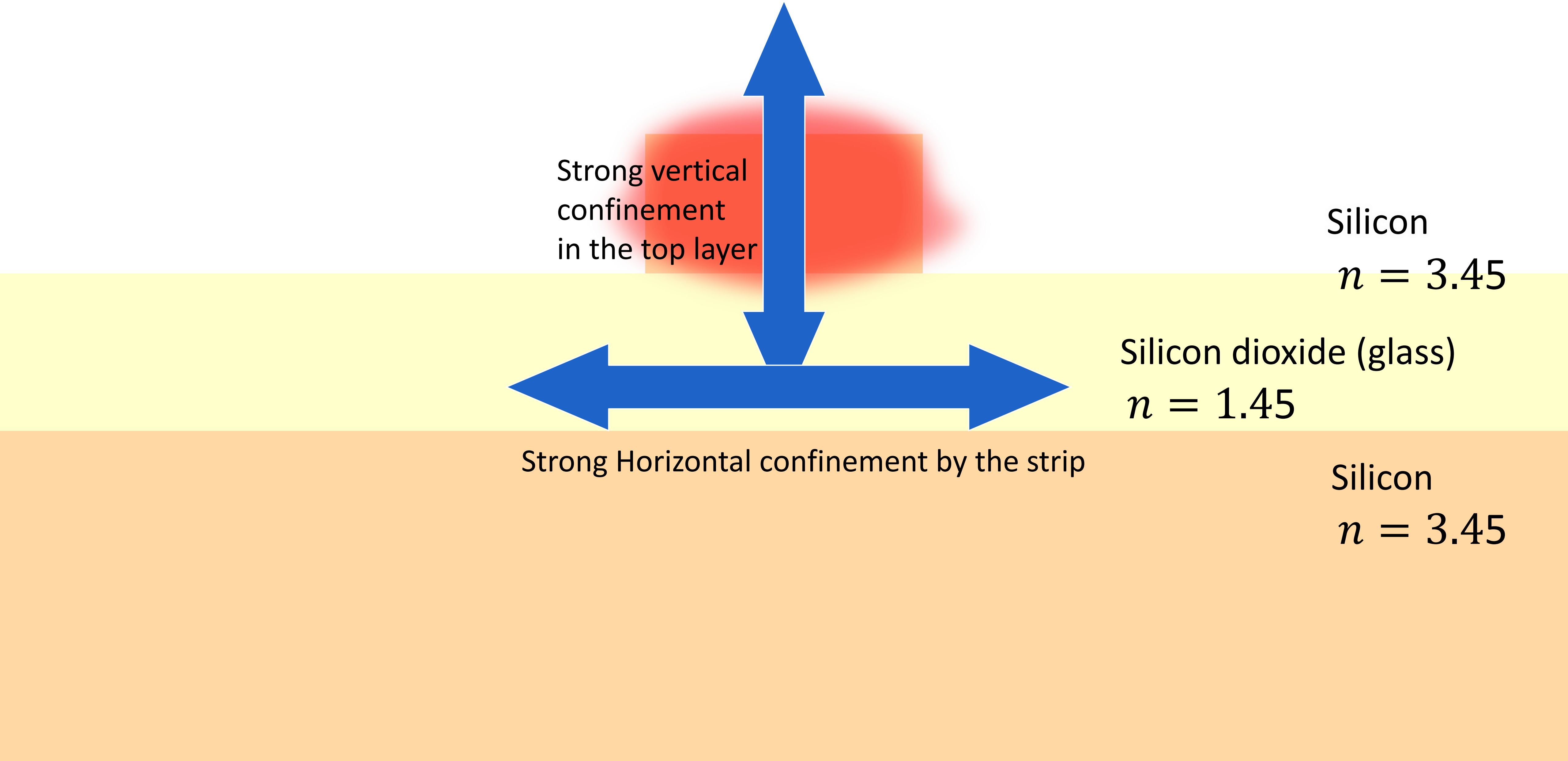
EARLY SILICON WAVEGUIDES



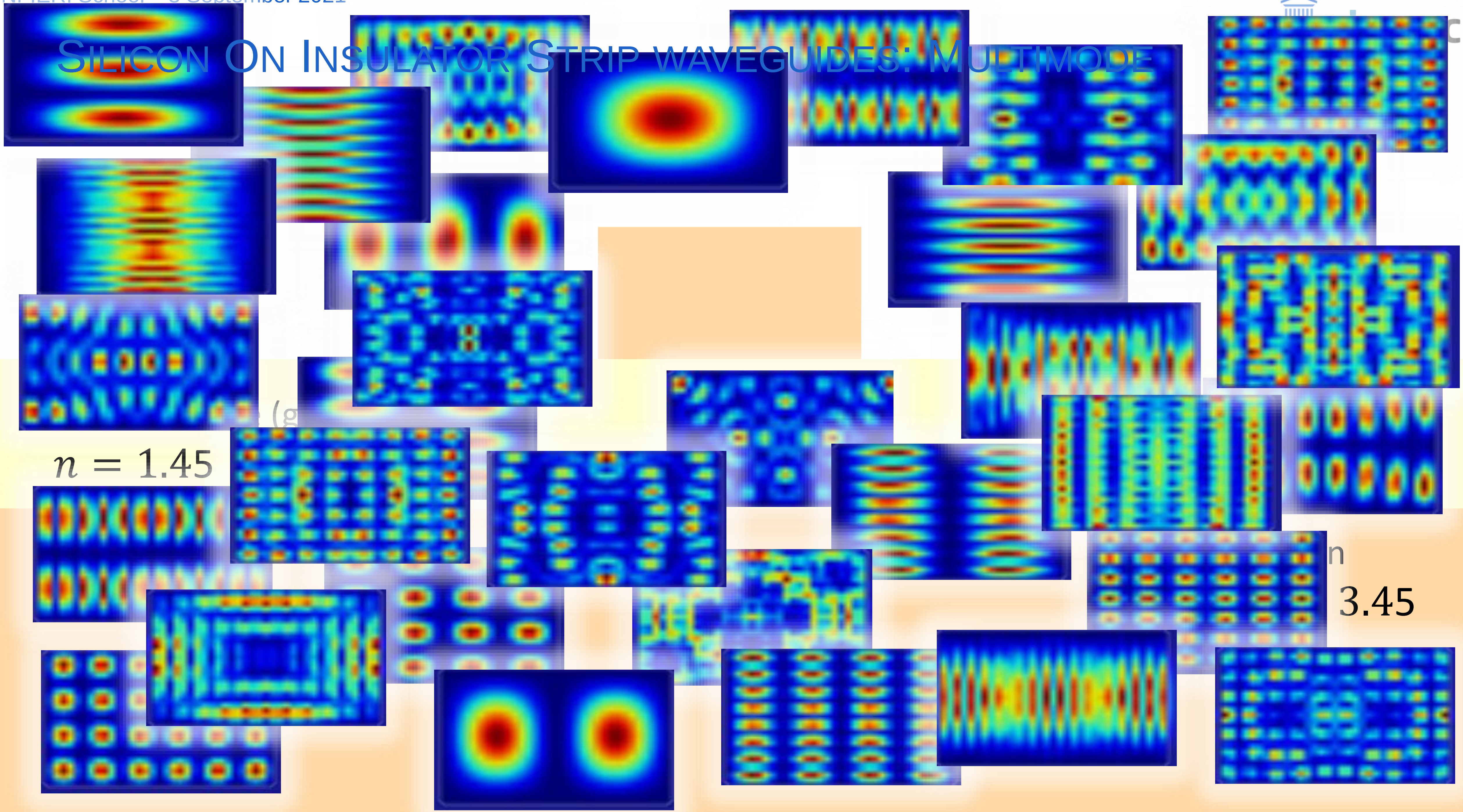
Silicon on insulator Rib waveguides



Silicon on Insulator Strip waveguides



Silicon On Insulator Strip waveguides: Multimode

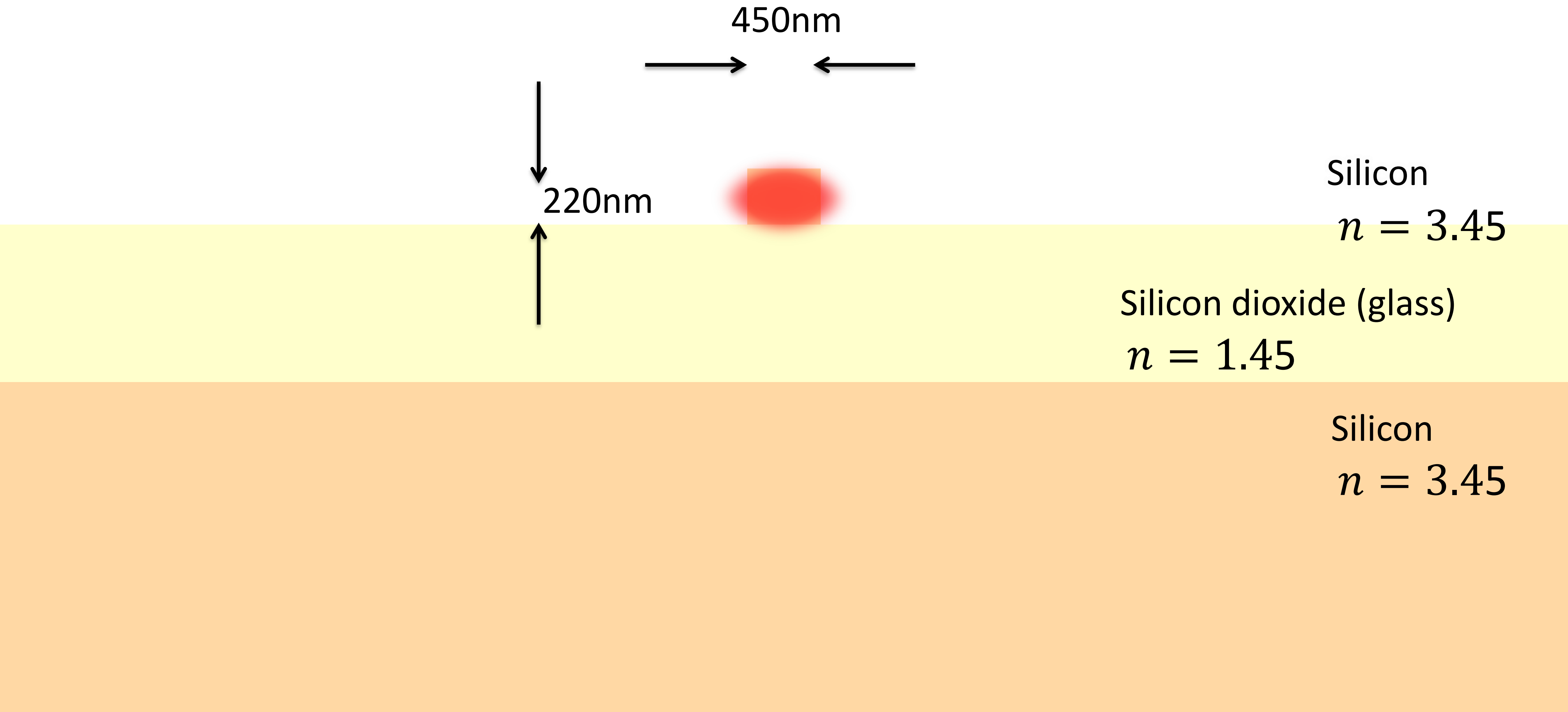


$n = 1.45$

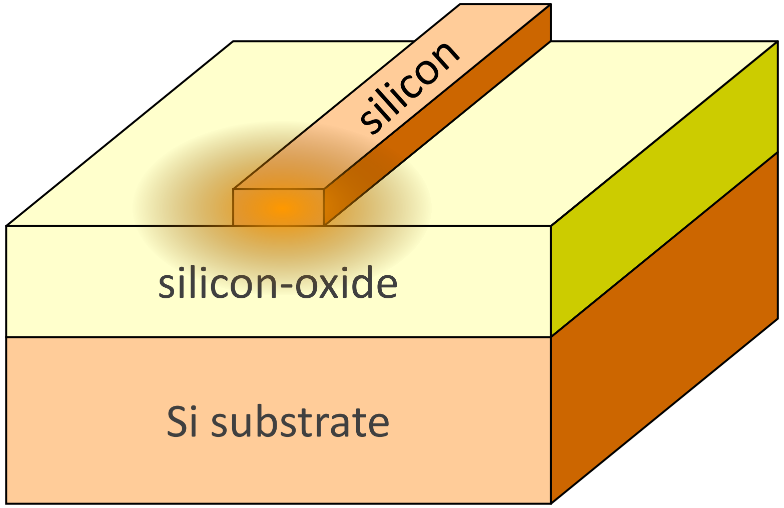
n

3.45

SHRINKING SOI WAVEGUIDES

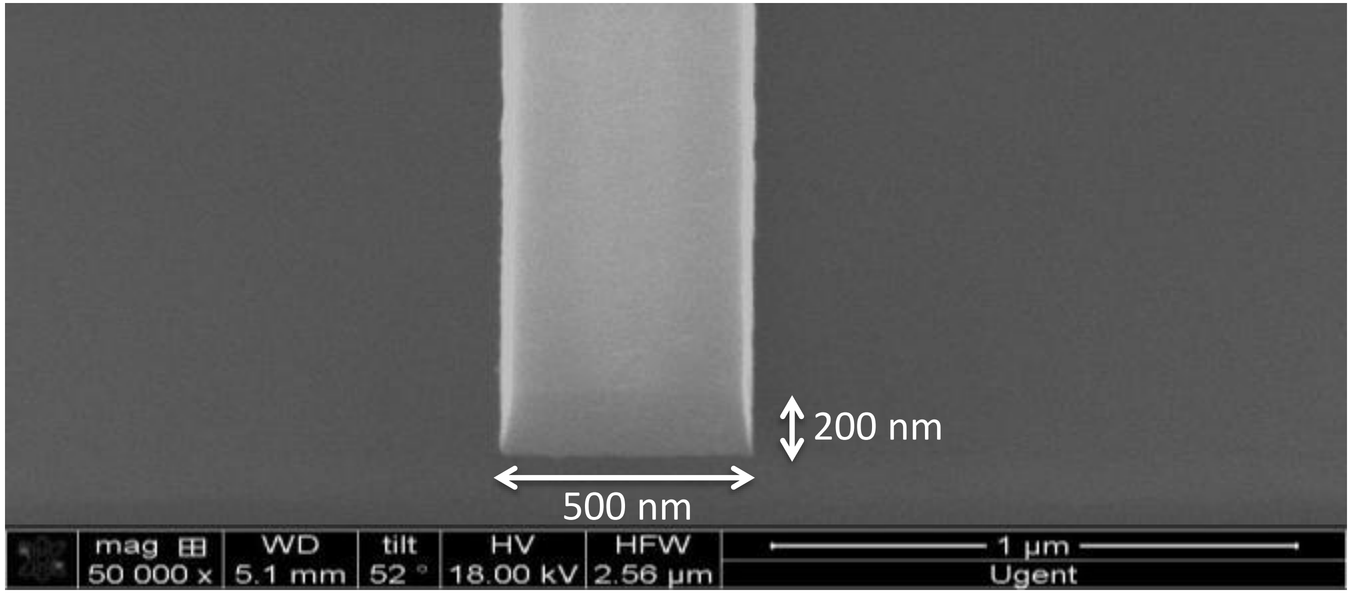


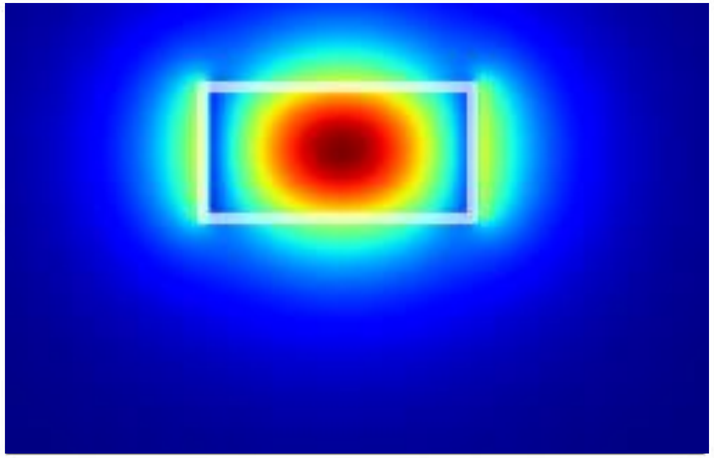
SILICON PHOTONIC WAVEGUIDES



$$n_{core} = 3.45$$
$$n_{cladding} = 1.45$$

High intensity on sidewalls

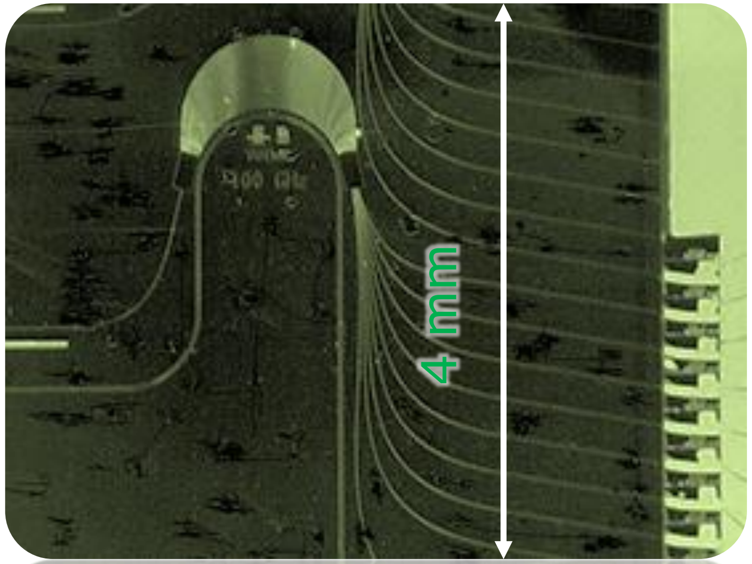




Higher contrast, smaller cores, tighter bends

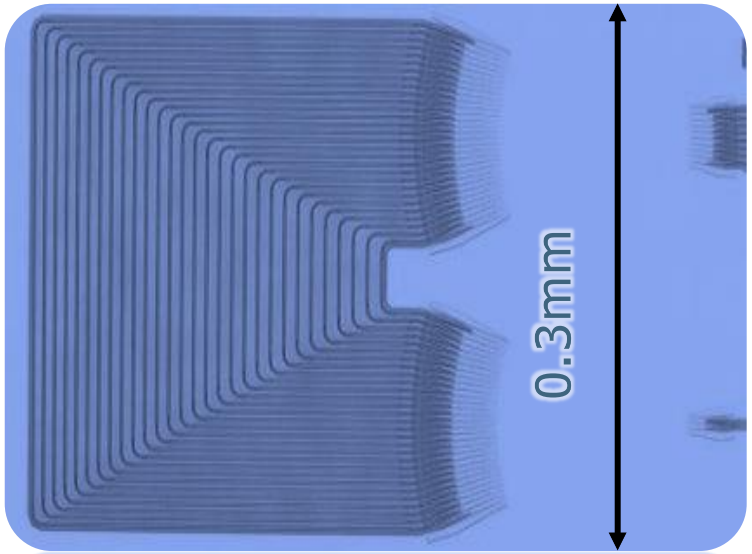
Silica on silicon

Contrast ~ 0.01 – 0.1
Mode diameter ~ 8µm
Bend radius ~ 5mm
Size ~ 10 cm^2



Indium Phosphide

Contrast ~ 0.2 – 0.5
Mode diameter ~ 2µm
Bend radius ~ 0.5mm
Size ~ 10mm^2



Silicon on insulator

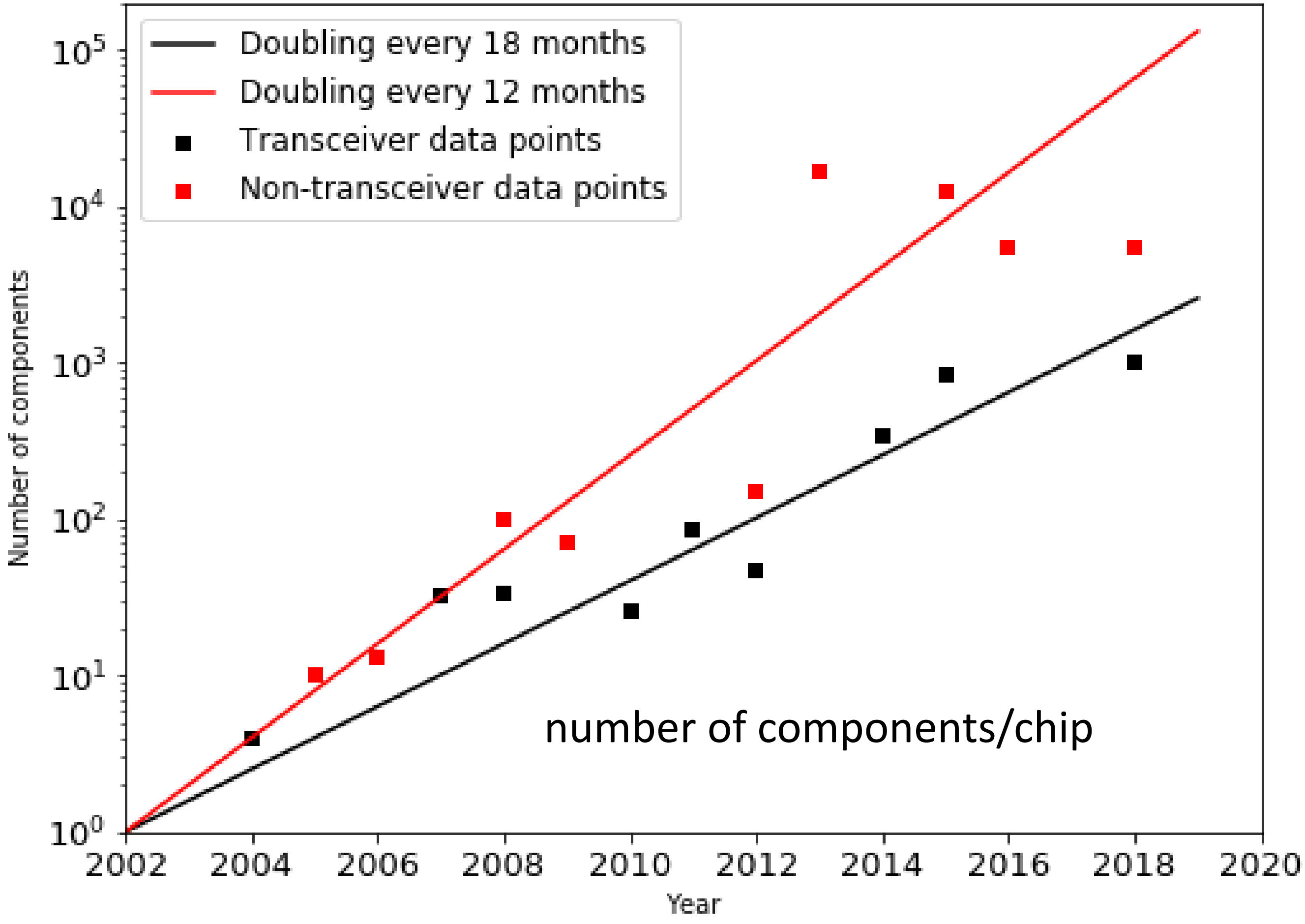
Contrast ~ 1.0 – 2.5
Mode diameter ~ 0.4µm
Bend radius ~ 5µm
Size ~ 0.1mm^2

10000 ×

SILICON PHOTONIC CIRCUIT SCALING

Rapidly growing integration

- O(1000) components on a chip
- photonics + electronic drivers
- different applications (mostly comms)
- Relatively small chip volumes (compared to electronics)



Khanna et al. 2016

WHY SILICON PHOTONICS?

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Large scale manufacturing

Scale

Submicron-scale waveguides

SILICON PHOTONICS

The implementation of high density photonic integrated circuits by means of CMOS process technology in a CMOS fab

Complex functionality, compact chips, low cost, high volumes

Silicon Photonics industrial landscape

YOLE Développement

Silicon Photonics Transceivers

Typical data rate: 100 Gb/s

Typical symbol rate: 25 GBaud

- PSM4 (4 parallel fibers)
- WDM (4 wavelengths)
- PAM4
- Coherent (2 polarisations + QPSK)
- Coherent (16-QAM)

Under development:

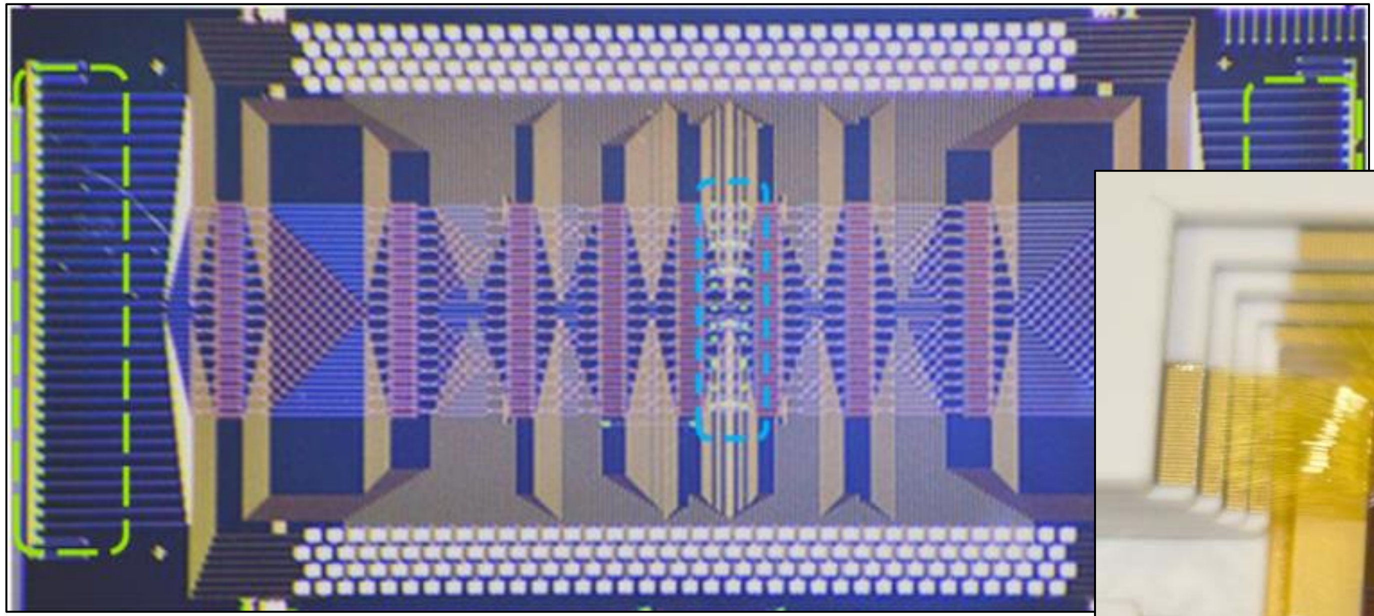
Data rate: 400-800 Gb/s

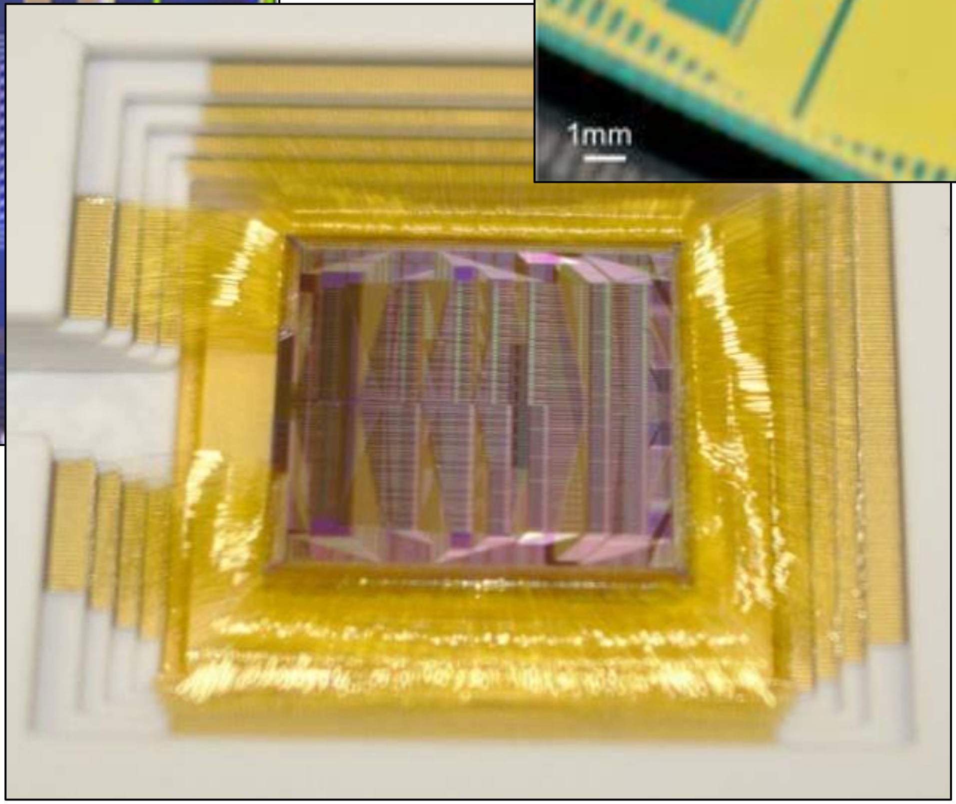
Symbol rate: 50-100 Gb/s

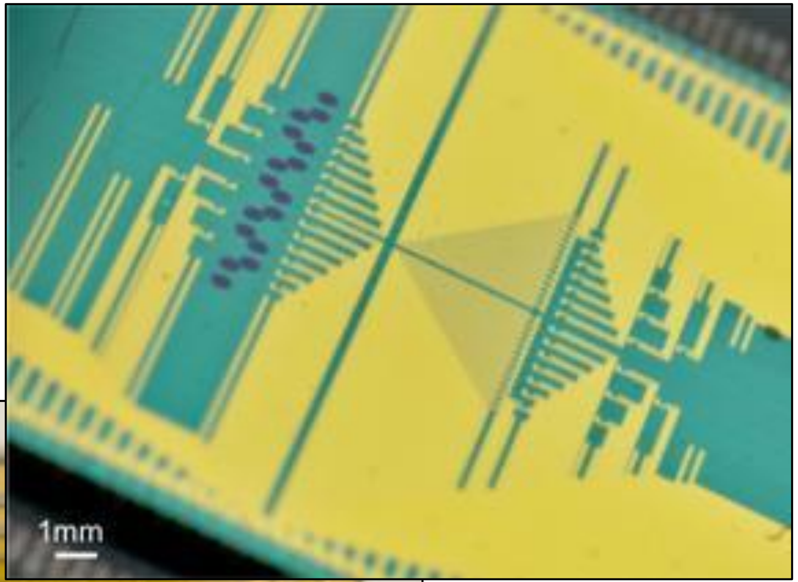
PHOTONIC LARGE-SCALE INTEGRATION IS HERE

That does not mean it is easy…

Larger circuits → lower fabrication yield?

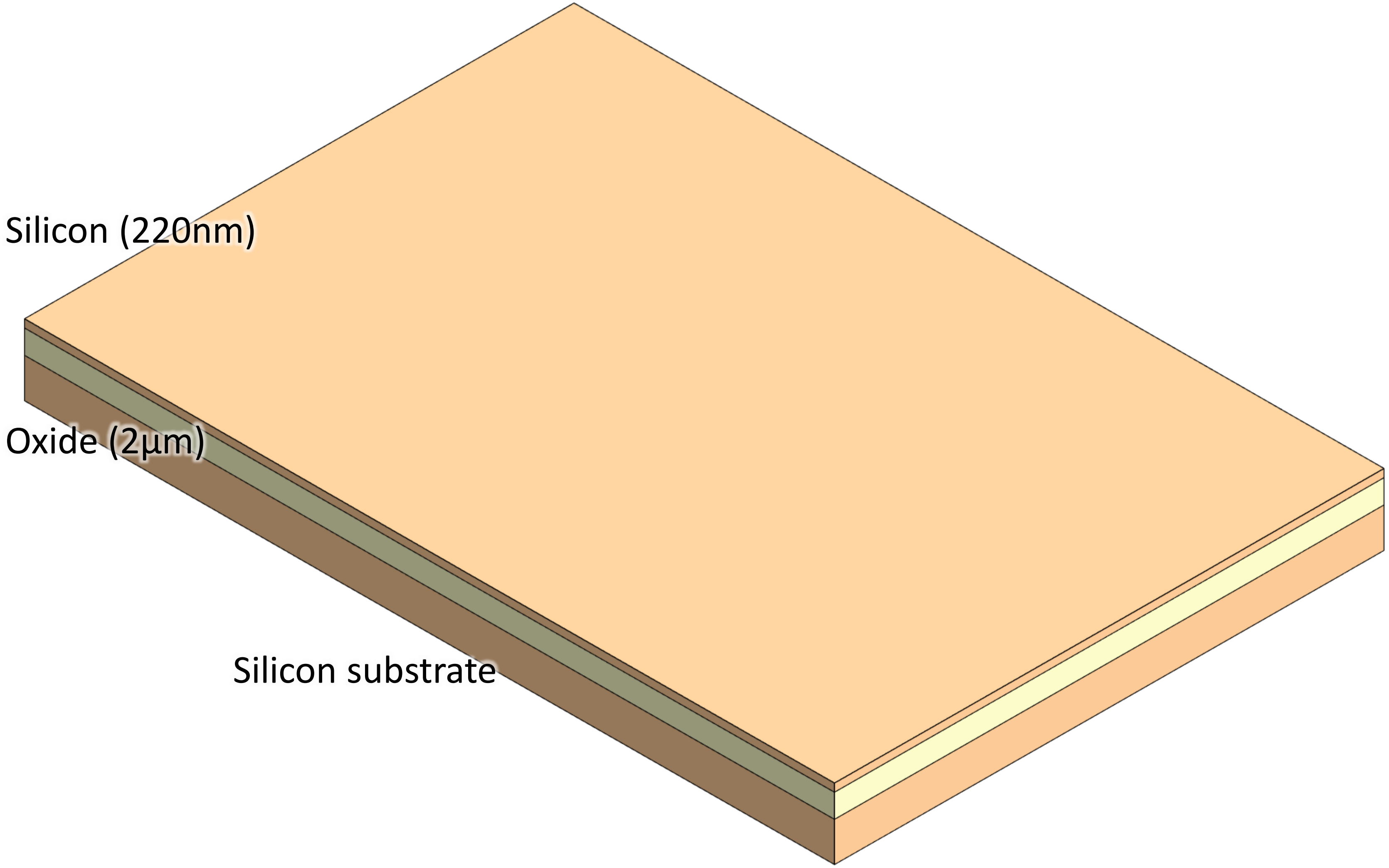






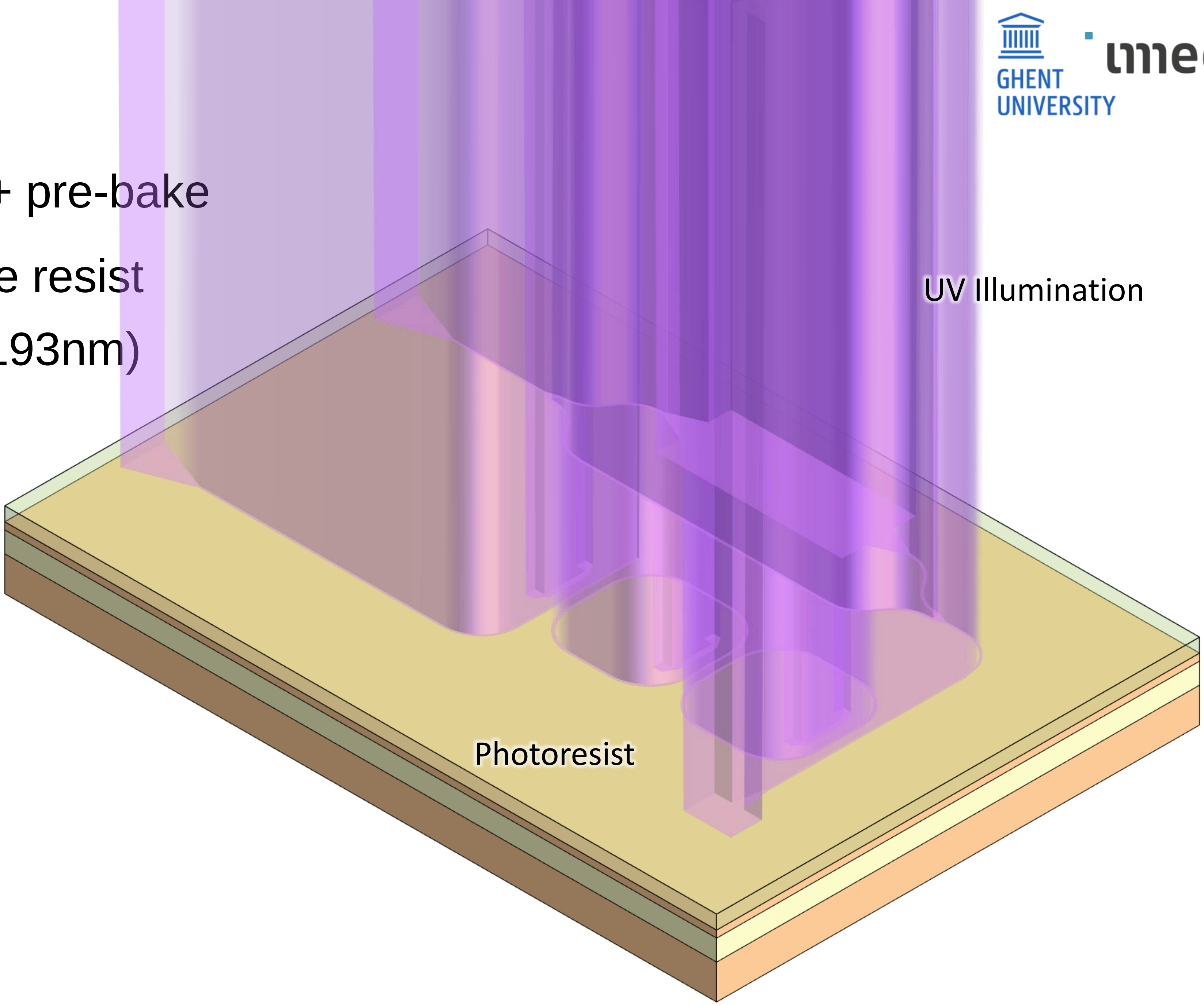
The Fabrication Process

BARE SILICON-ON-INSULATOR WAFER



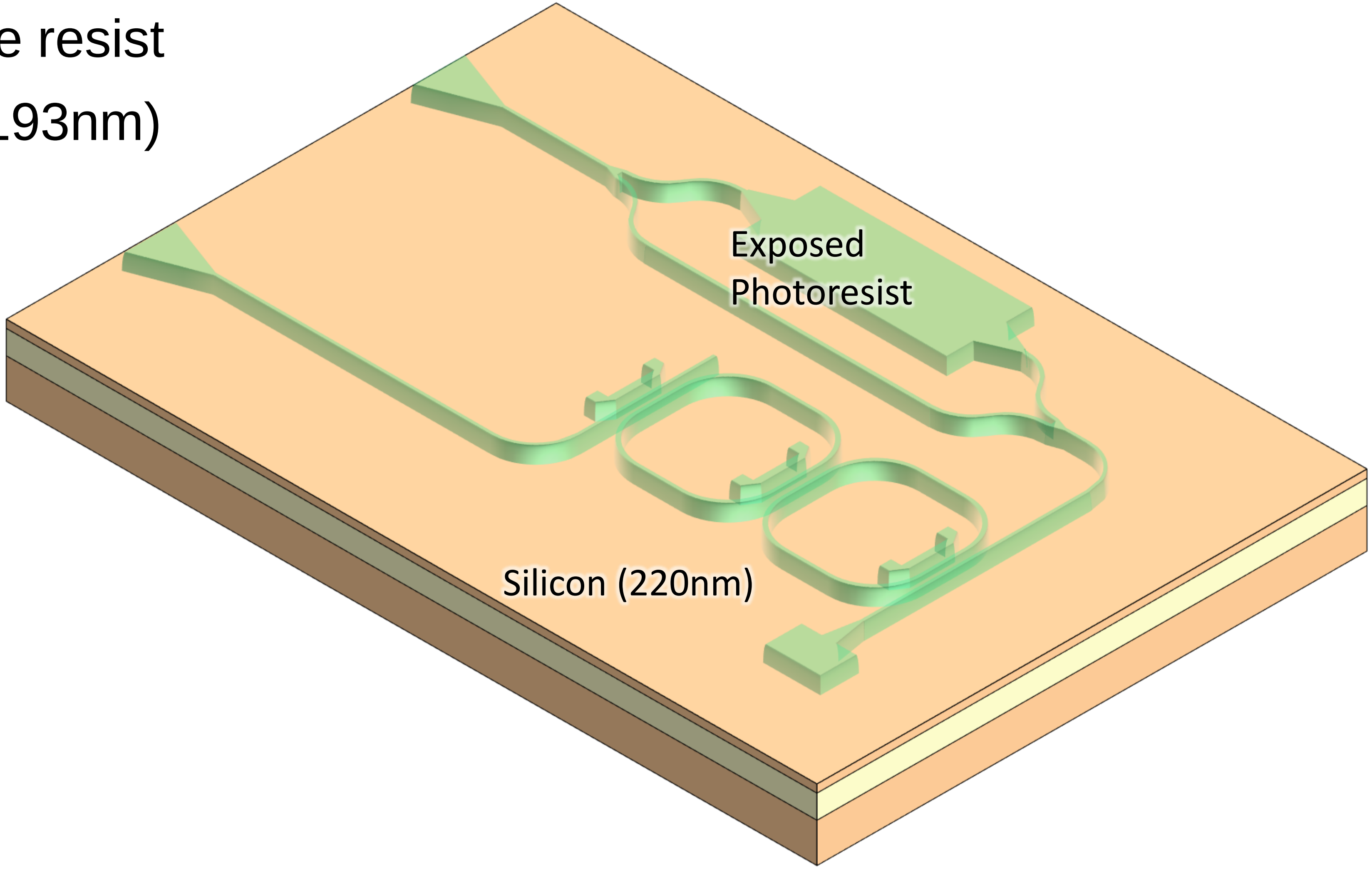
PHOTOLITHOGRAPHY

1. Spin-coat Photoresist + pre-bake
2. Mask is projected in the resist (UV light at 248nm or 193nm)



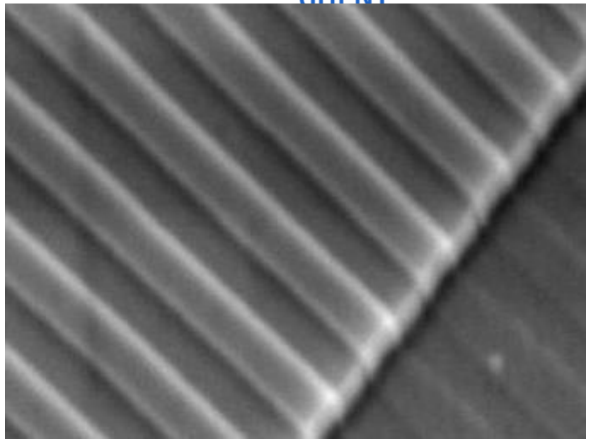
PHOTOLITHOGRAPHY

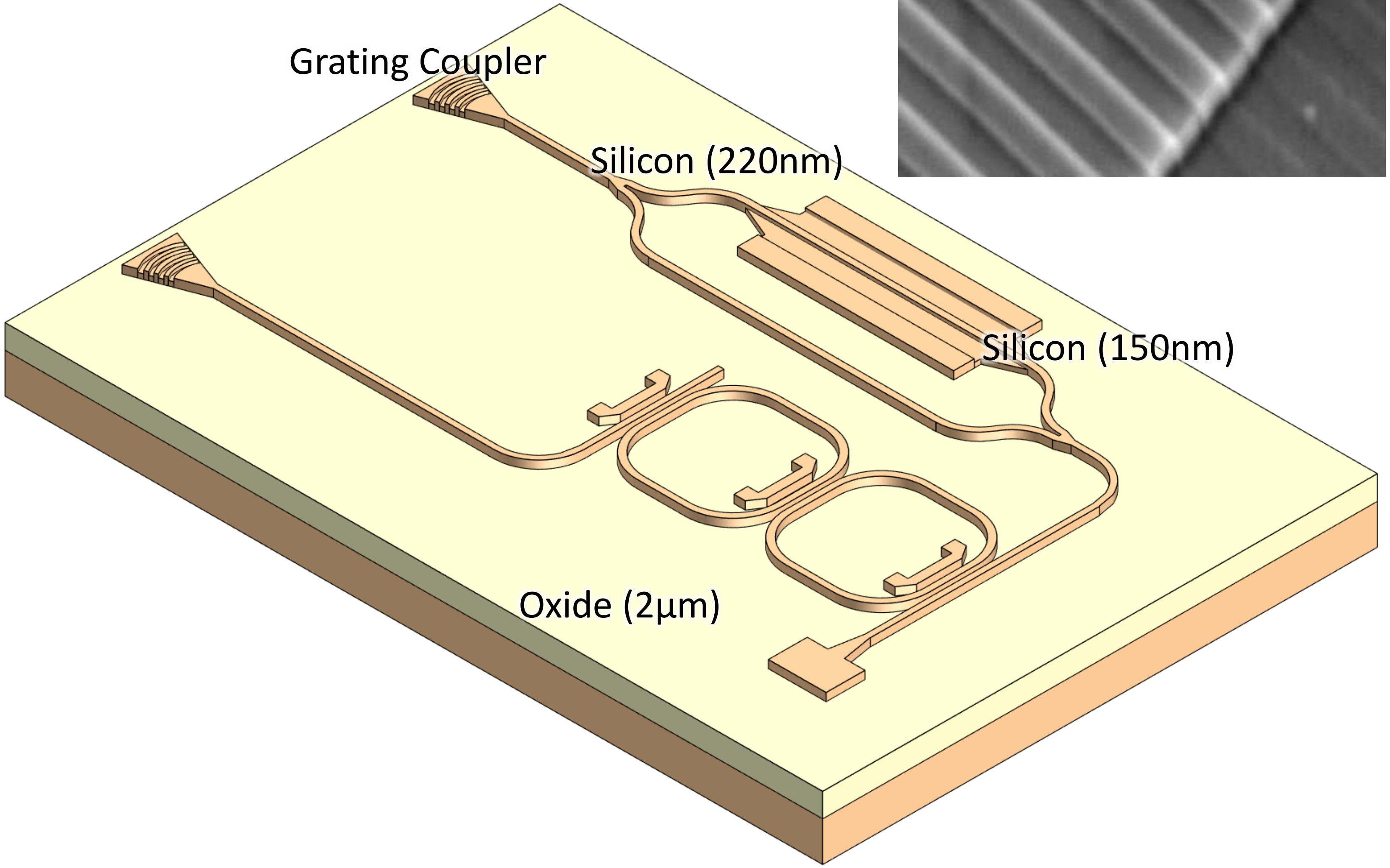
1. Spin-coat Photoresist + pre-bake
2. Mask is projected in the resist
   (UV light at 248nm or 193nm)
3. Post-Exposure bake
4. Resist is developed



Partial Silicon Etching

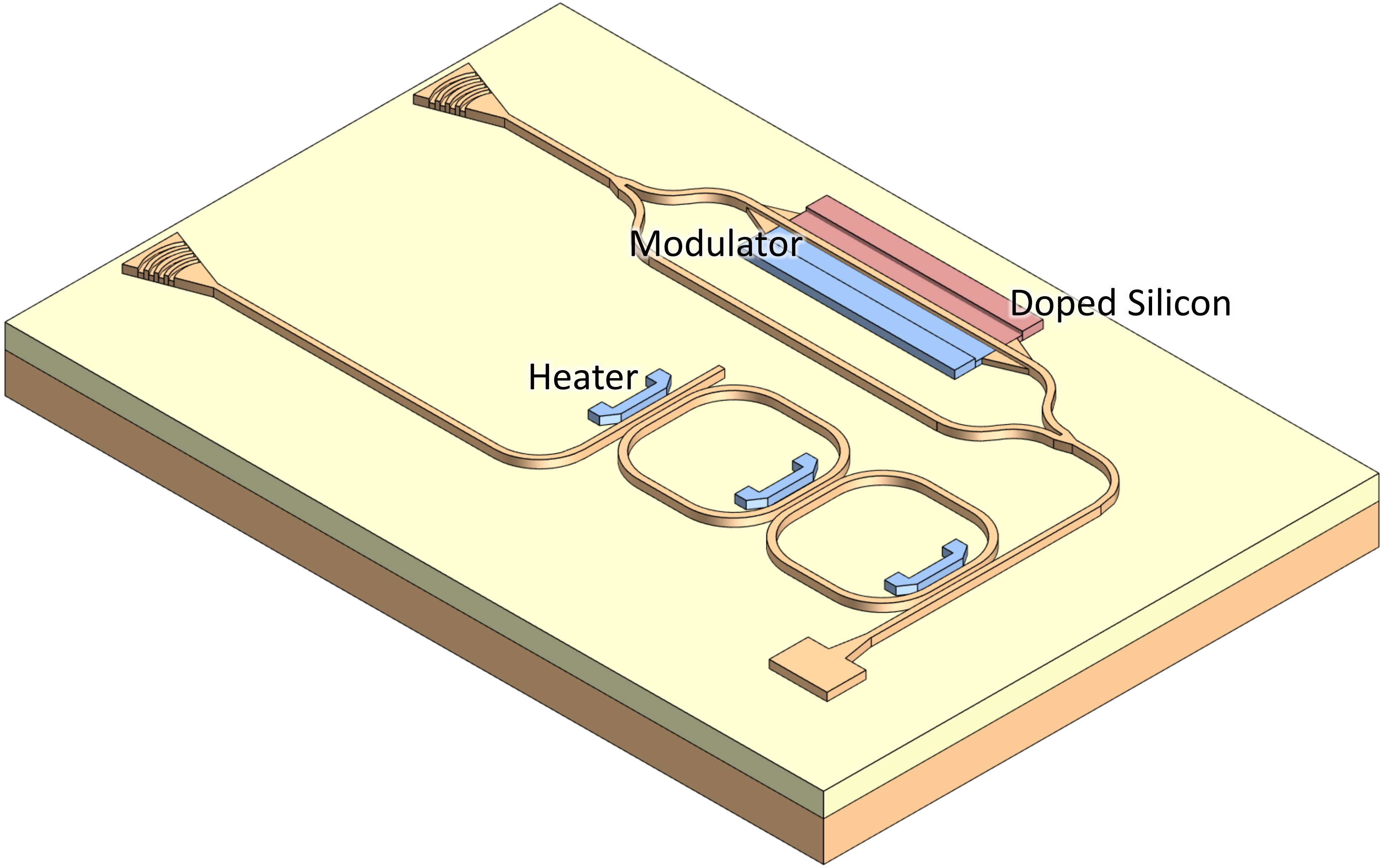
1. Lithography of second layer
2. Plasma etching
3. Resist Stripping





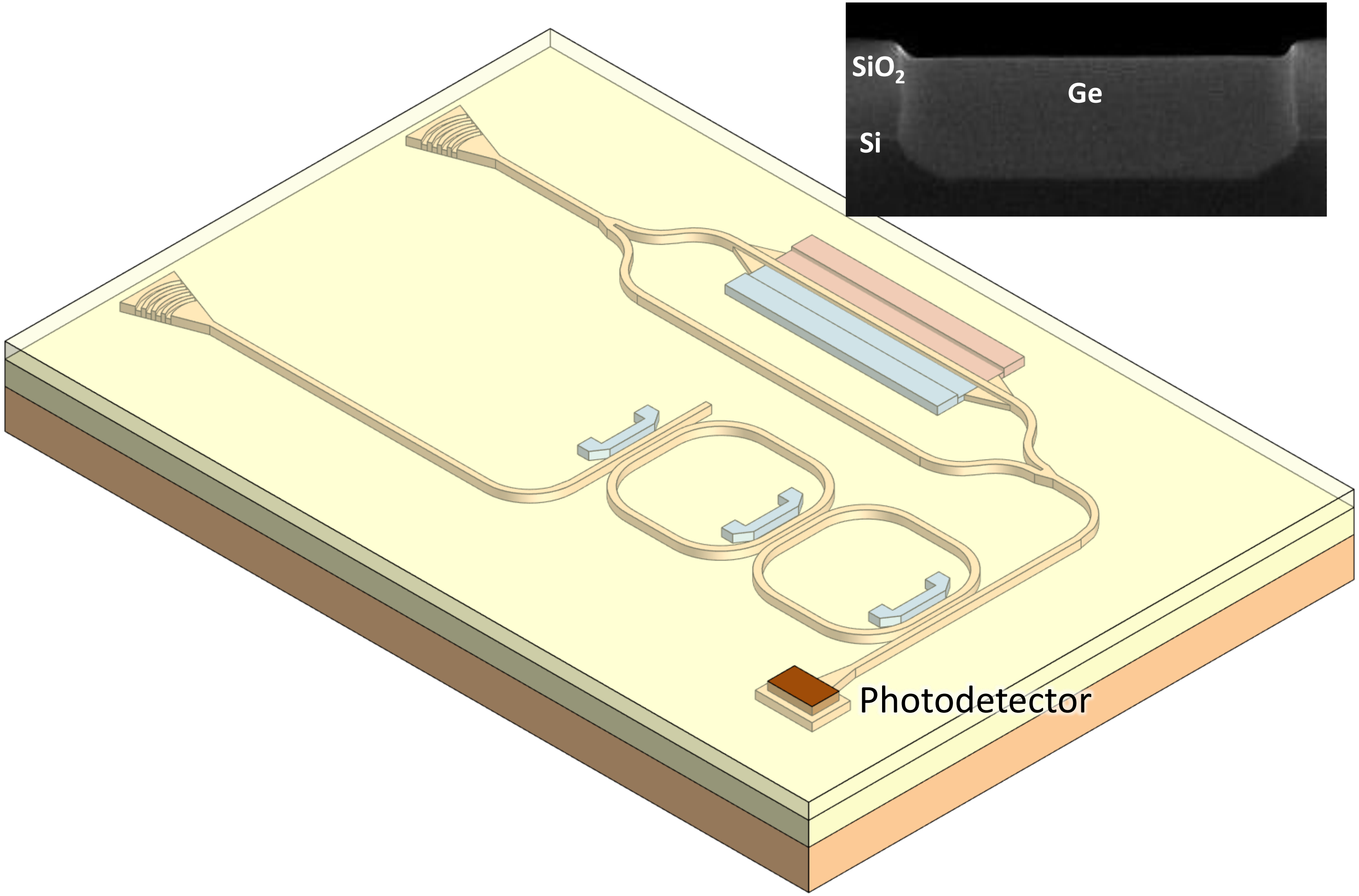
Doped regions for Modulators and Heaters

1. Lithography of windows
2. Ion implantation
3. Resist Stripping



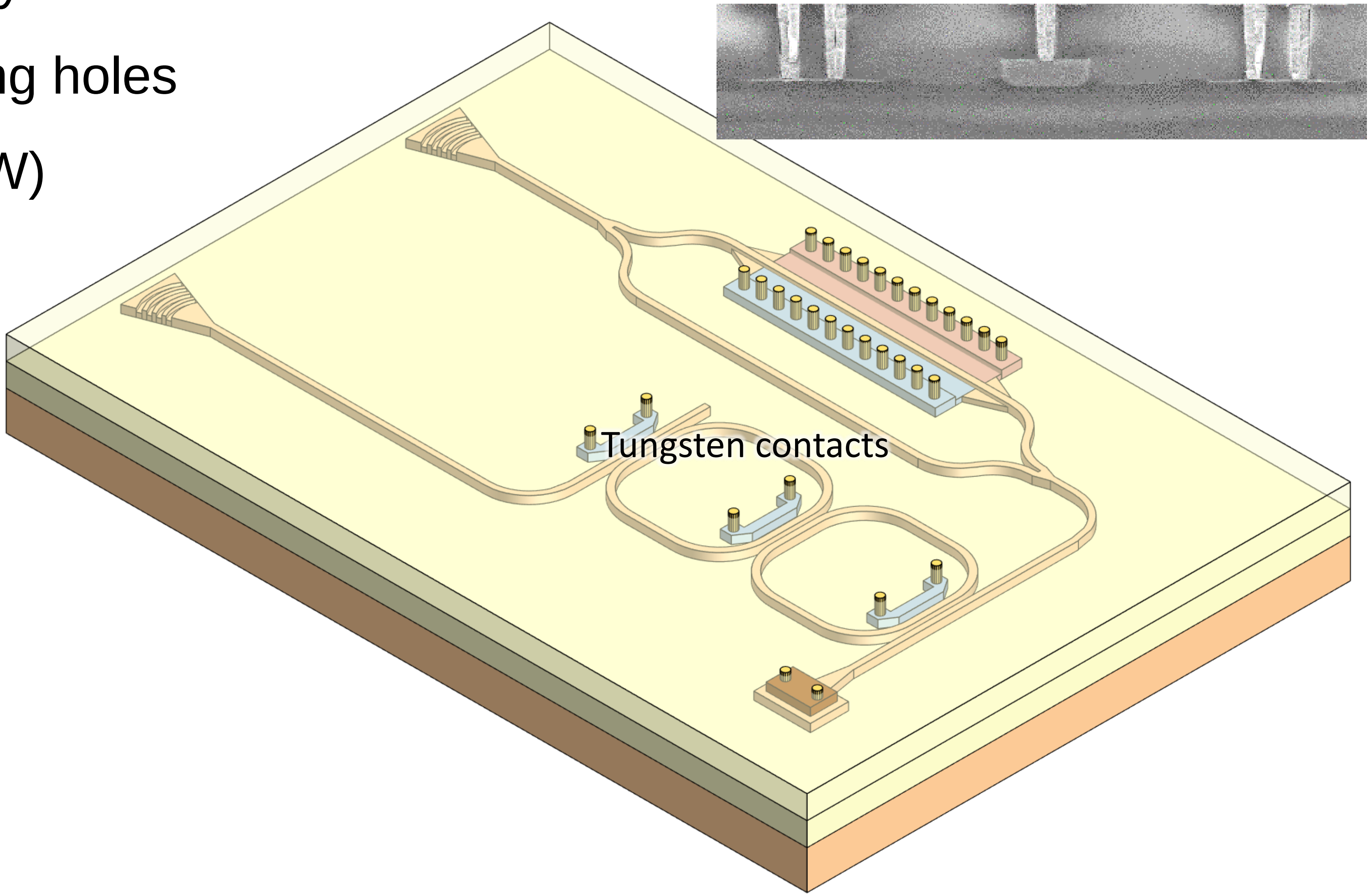
GERMANIUM PHOTODETECTORS

1. Oxide cladding
2. Planarization (CMP)
3. Opening of window
4. Epitaxial Growth of Ge
5. Planarization (CMP)



ELECTRICAL CONTACTS: DAMASCENE PROCESS

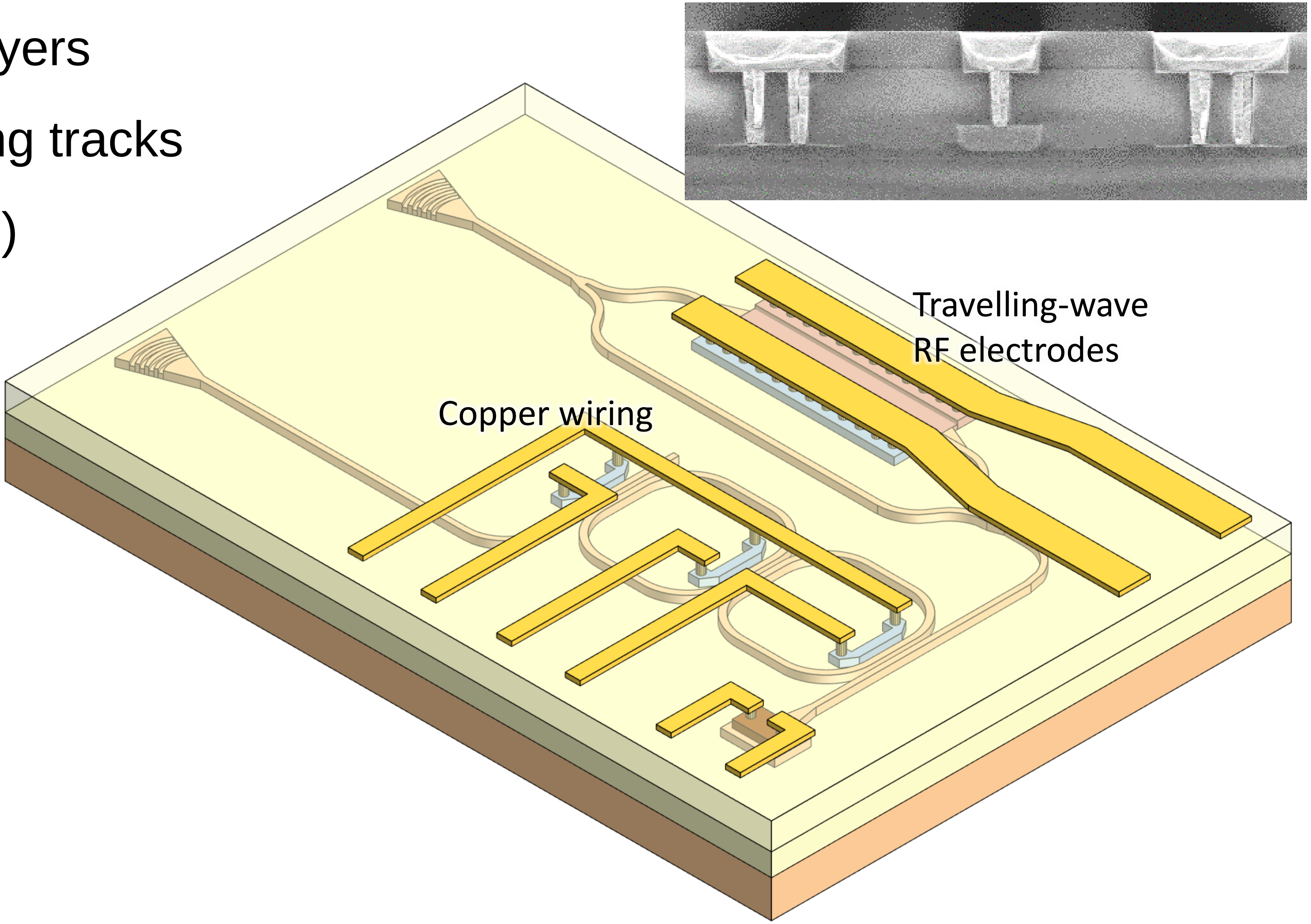
1. Depositing dielectric layers
2. Lithography and Etching holes
3. Filling with Tungsten (W)
4. Planarization (CMP)



Metal Interconnects: Damascene process

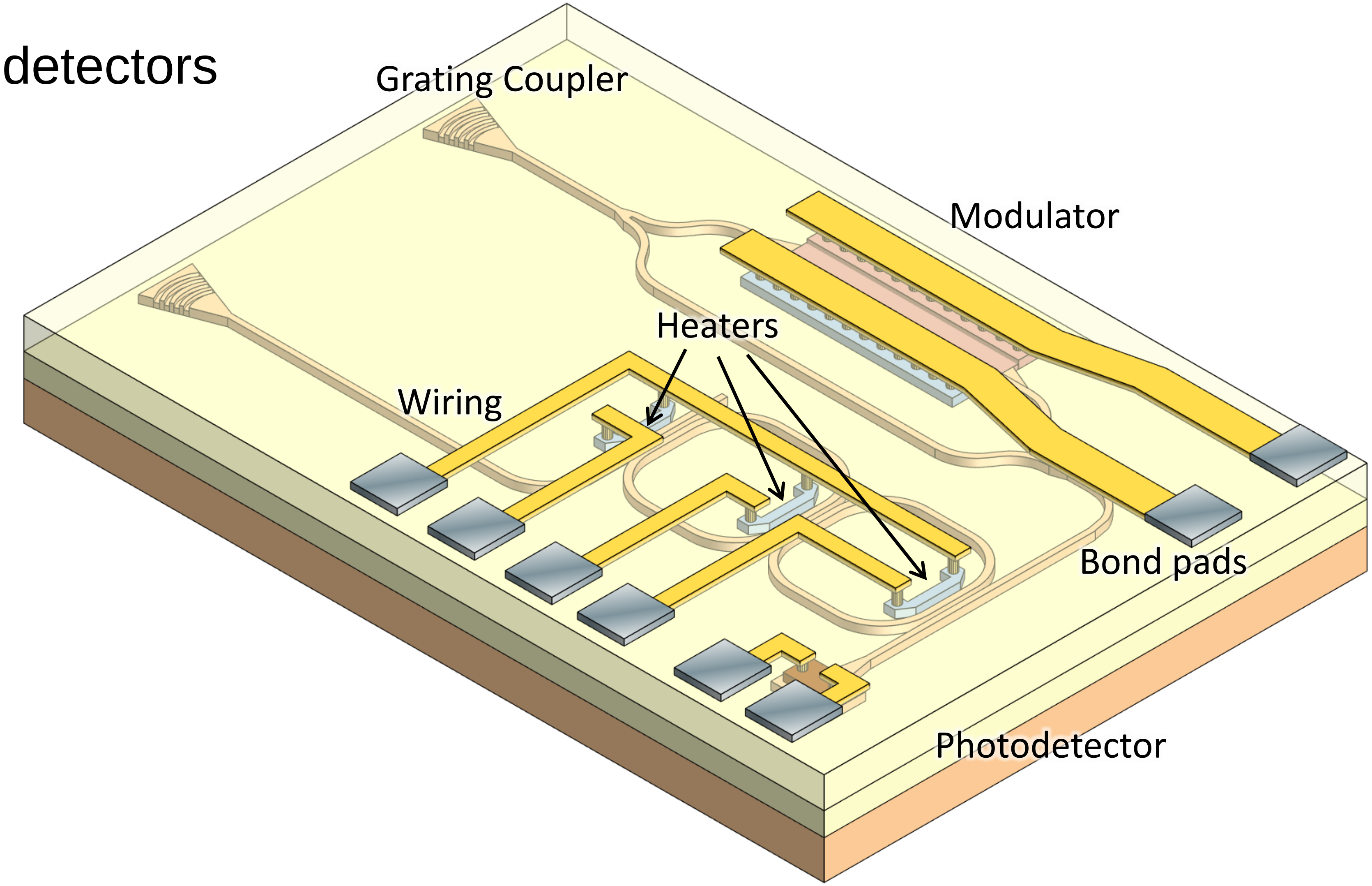
1. Depositing dielectric layers
2. Lithography and Etching tracks
3. Filling with Copper (Cu)
4. Planarization (CMP)

Repeat for more layers

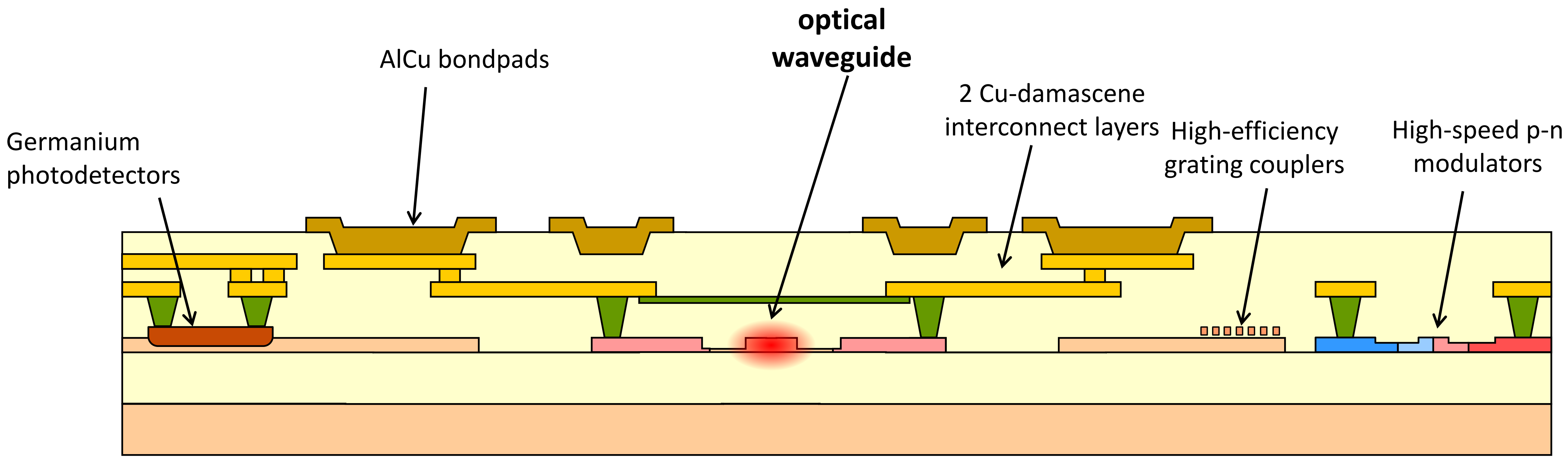


SILICON PHOTONICS CHIPS

1. Passive circuits with multiple etch layers
2. Modulators and Photodetectors
3. Metal wiring



IMEC's iSiPP50G Platform



Low-loss rib and strip waveguides

Multiple types of Integrated heaters

p(i)n junction modulators

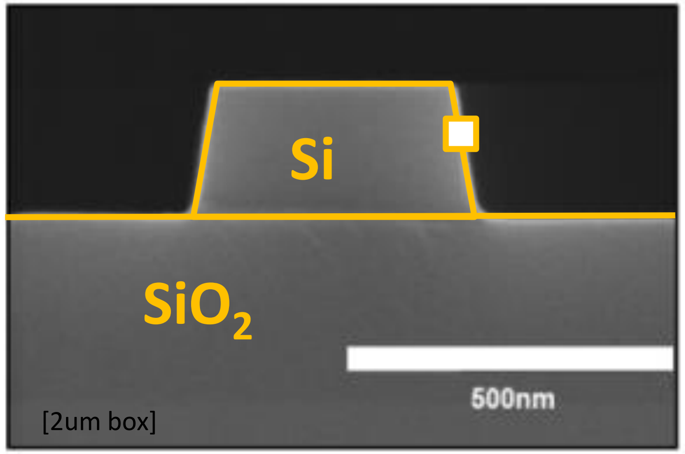
Germanium photodetectors

Pantouvaki, JLT 2017

HIGH INDEX CONTRAST: A BLESSING AND A CURSE

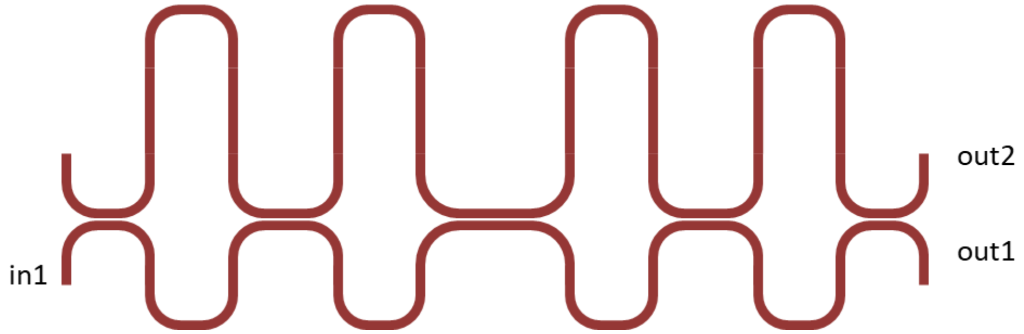
Every nm^3 matters

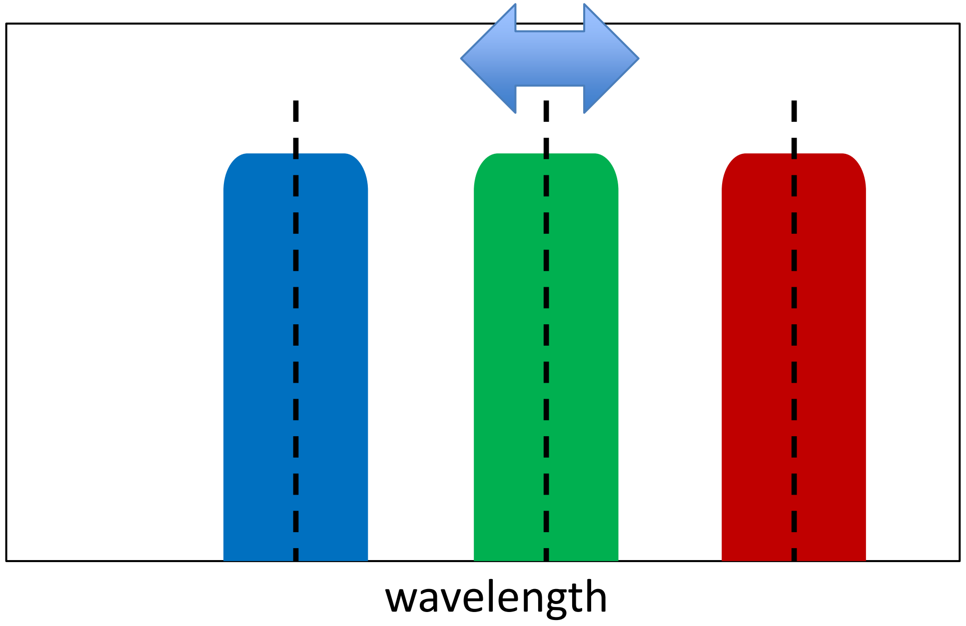
CMOS technology is the only manufacturing technology with sufficient nm-process control to take advantage of the blessing without suffering from the curse



Sensitivity of Silicon Photonics Wavelength Filters

Especially wavelength filters are sensitive

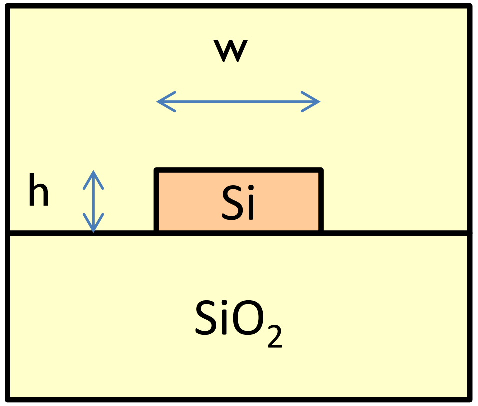




wire width $\frac{\partial\lambda}{\partial w} \approx 1\, {}^{nm}/_{nm}$

wire height $\frac{\partial\lambda}{\partial h} \approx 2\, {}^{nm}/_{nm}$

temperature $\frac{\partial\lambda}{\partial T} \approx 0.08\, {}^{nm}/_{K}$

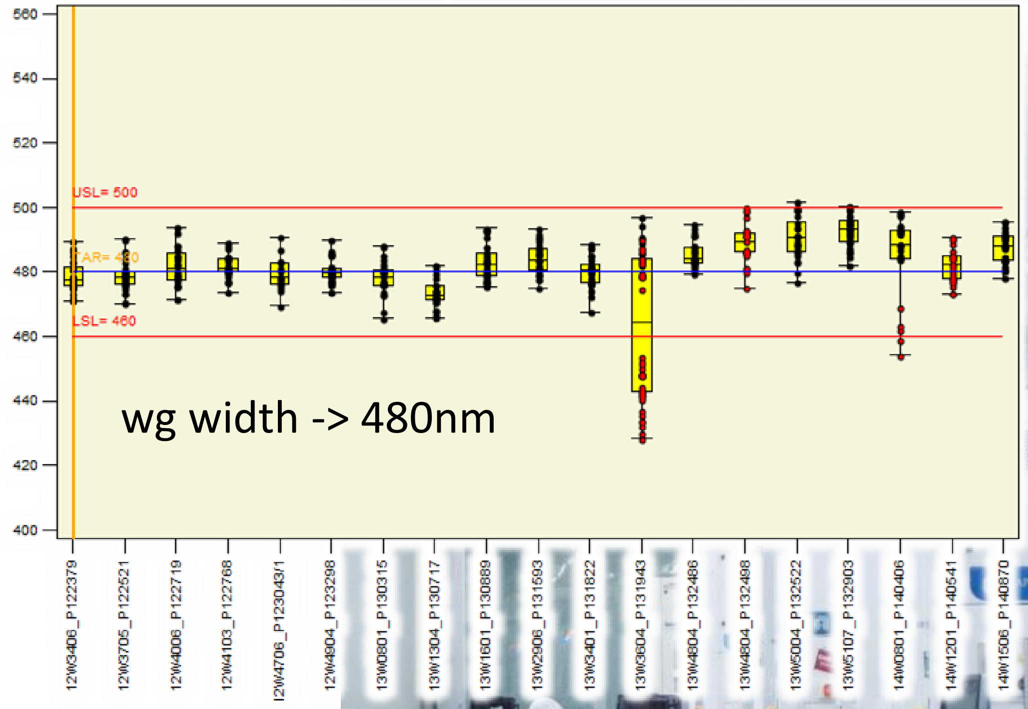


Coping with Variability: Improved fabrication

Use more advanced fabs

- better tools
- higher resolution
- better wafers

statistical process control



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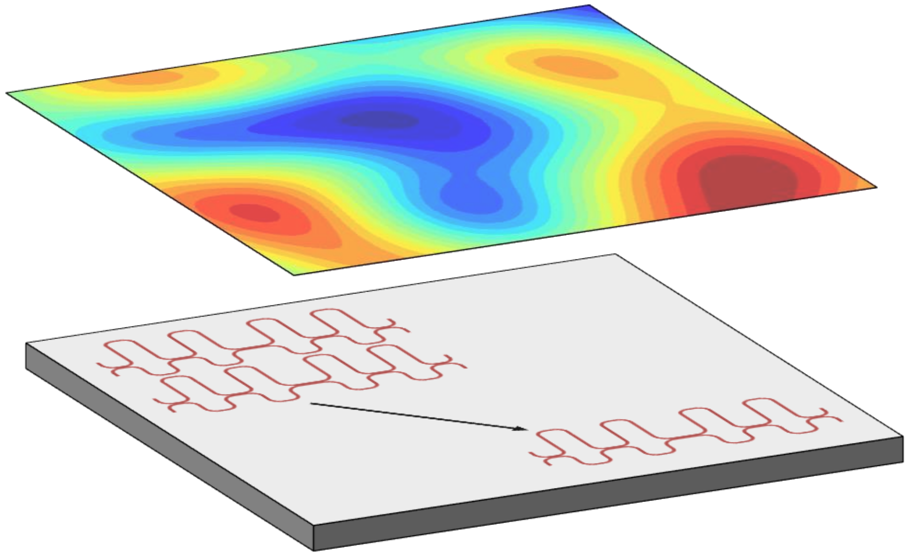
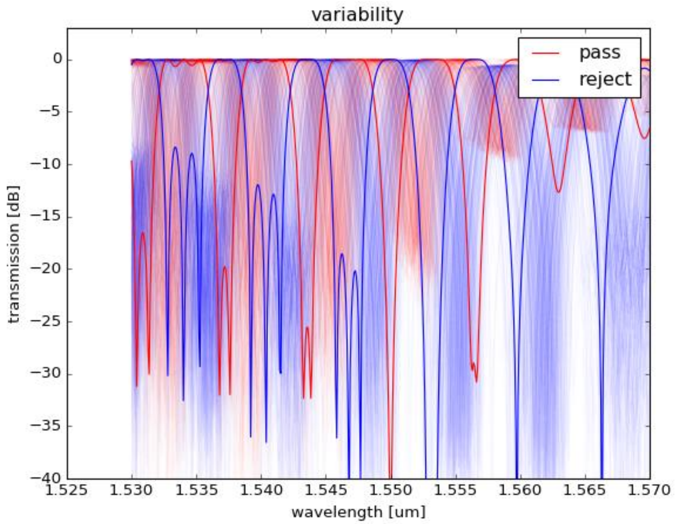
Coping with Variability: Variability-Aware Design

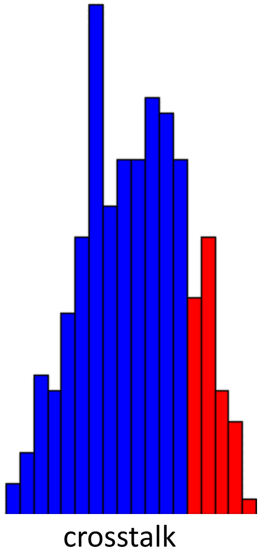
propagating variability at component level to circuit level

- accurate circuit models
- sensitivity of the components
- wafer-scale distribution of variability

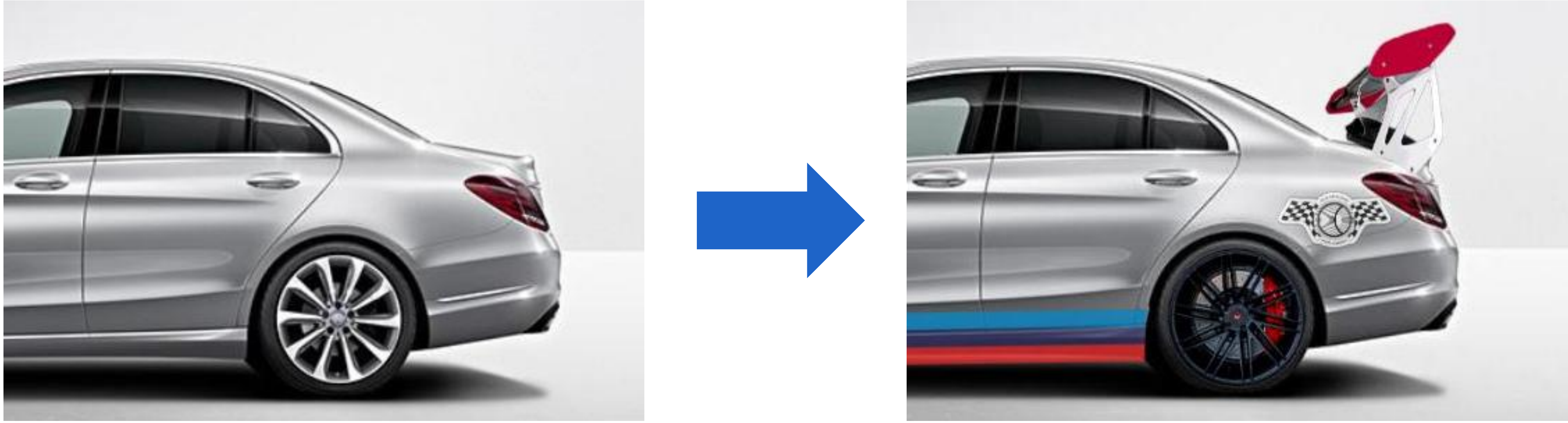
Monte-Carlo methods or Stochastic Methods







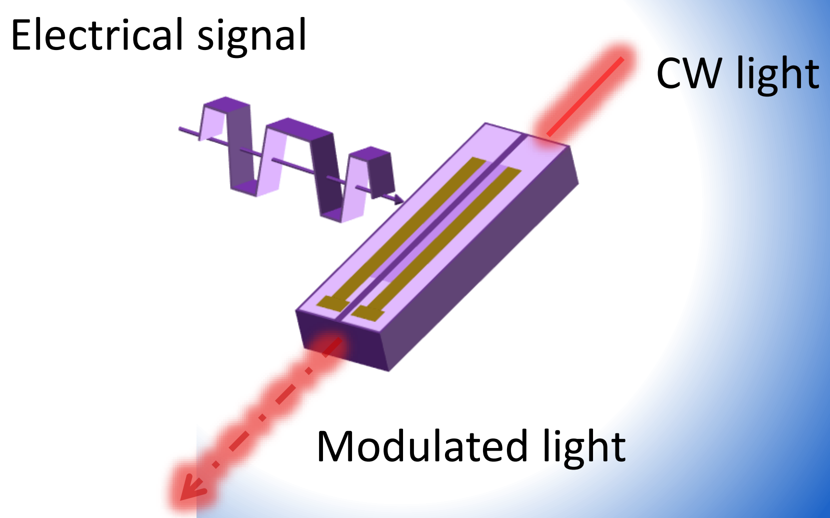
COPING WITH VARIABILITY: TUNING



Actively compensate for mismatches in fabrication

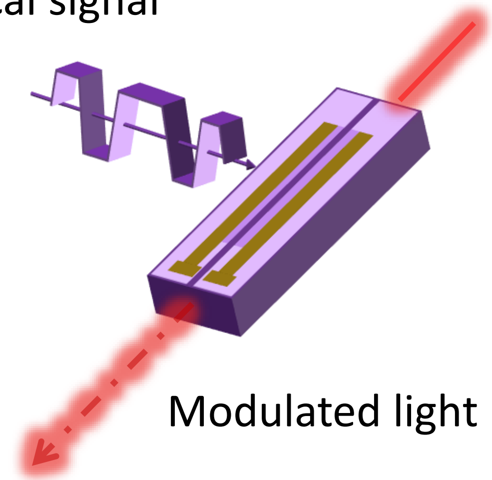
Make everything tunable

- add tuning elements within your circuit
- add active electronic control



Electro-Optic Actuators

ELECTRICAL MODULATION, SWITCHING AND TUNING



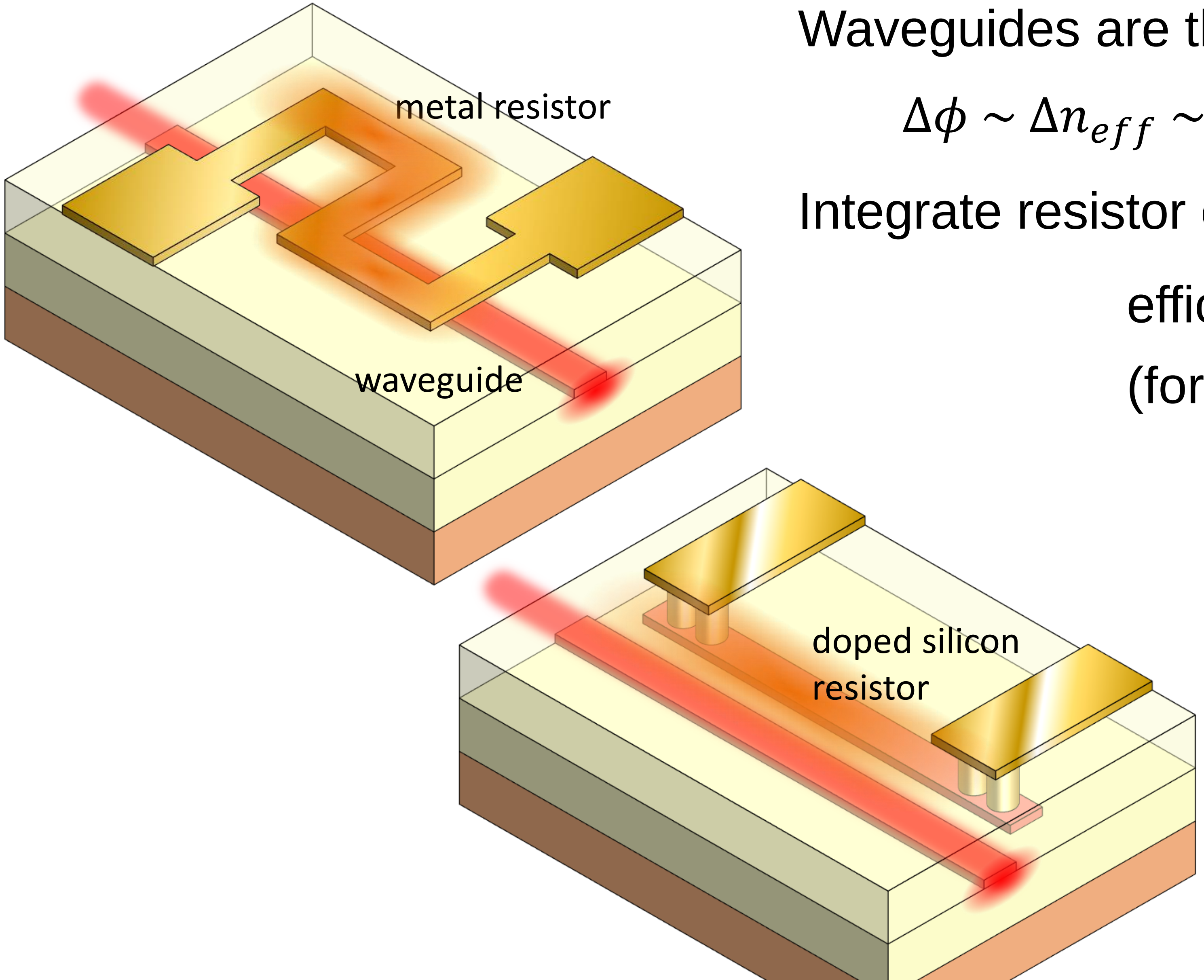
Electrical actuation:

- Thermal
- Carrier injection/extraction
- Electro-optics

Different applications:

- Tuning: slow, analog
- Switching: slow, digital (<kHz), full amplitude
- Signal modulation: fast (GHz – 100GHz)
    - amplitude
    - phase

The basic Optical Phase shifter: A Heater



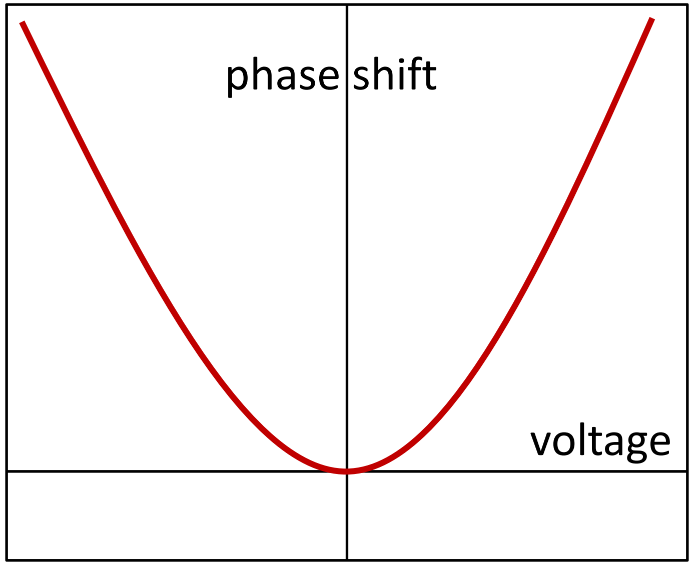
Waveguides are thermally sensitive:

$$\Delta\phi \sim \Delta n_{eff} \sim T \sim P_{elec} \sim V^2 \sim I^2$$

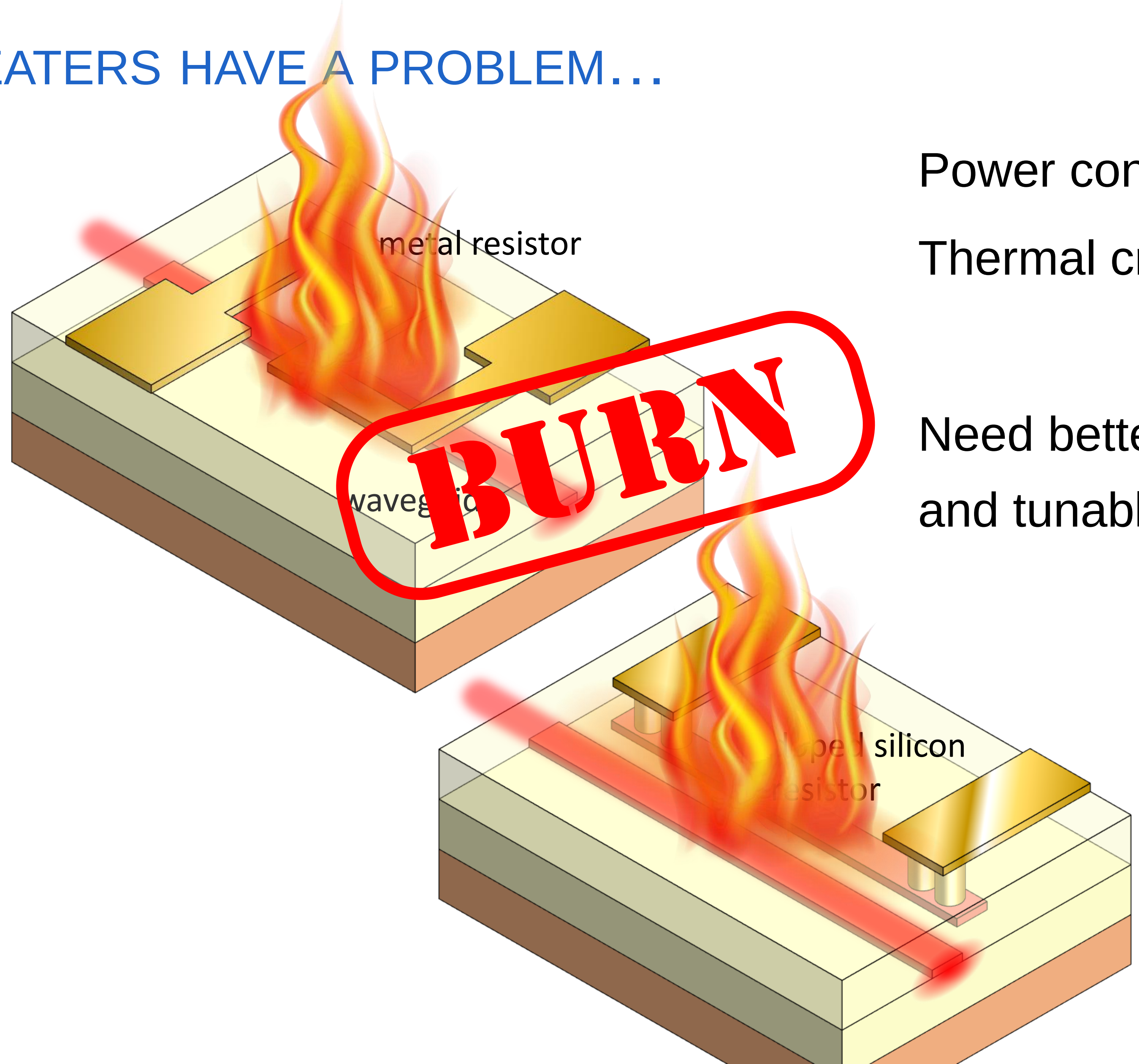
Integrate resistor close to the waveguide

efficiency: $P_\pi \approx 5 - 30mW$

(for silicon waveguides)



HEATERS HAVE A PROBLEM…



Power consumption

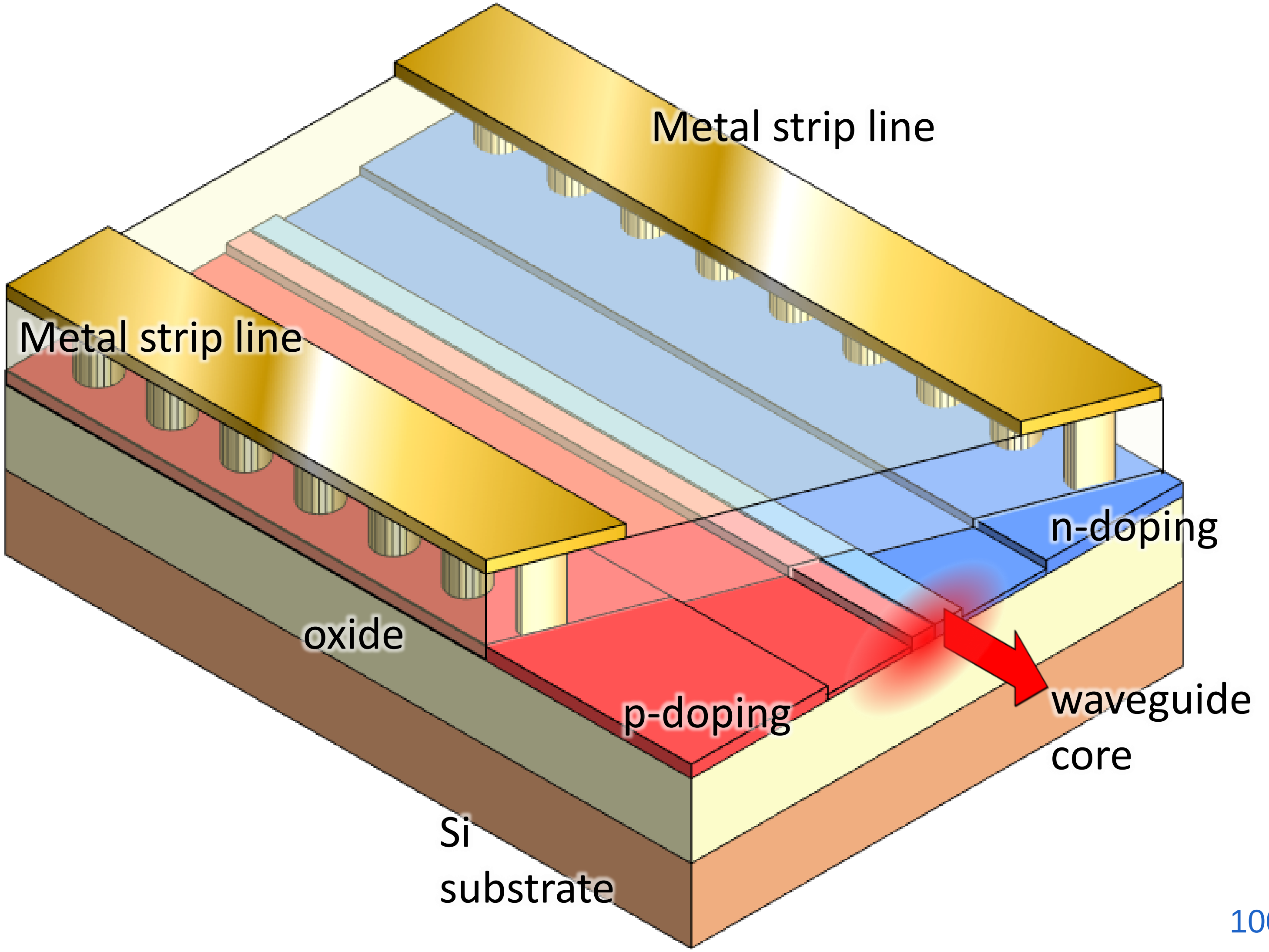
Thermal crosstalk

Need better phase shifters
and tunable couplers

FAST SIGNAL MODULATION: CARRIERS

Add doped junction to silicon waveguide:

modulate refractive index

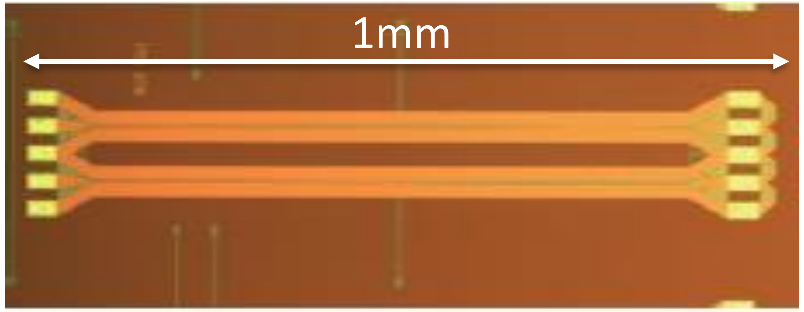


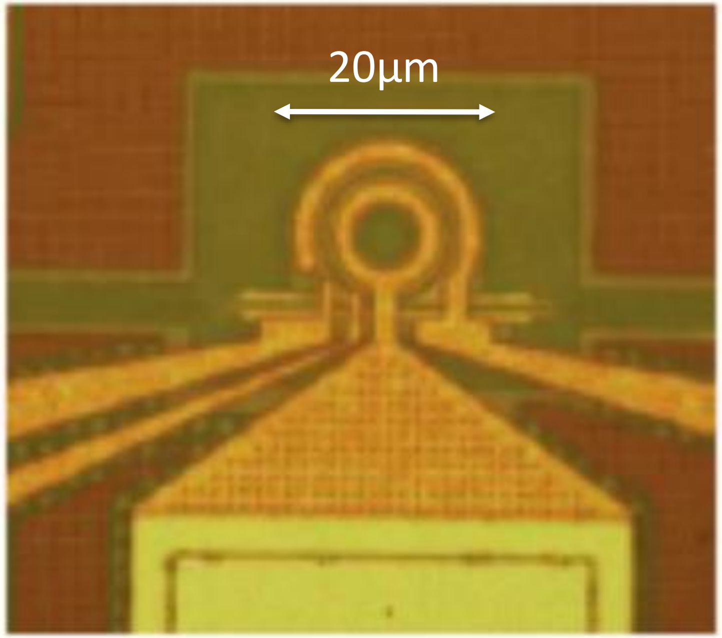
ELECTRICAL SIGNAL MODULATION

Add doped junction to silicon waveguide:

modulate refractive index

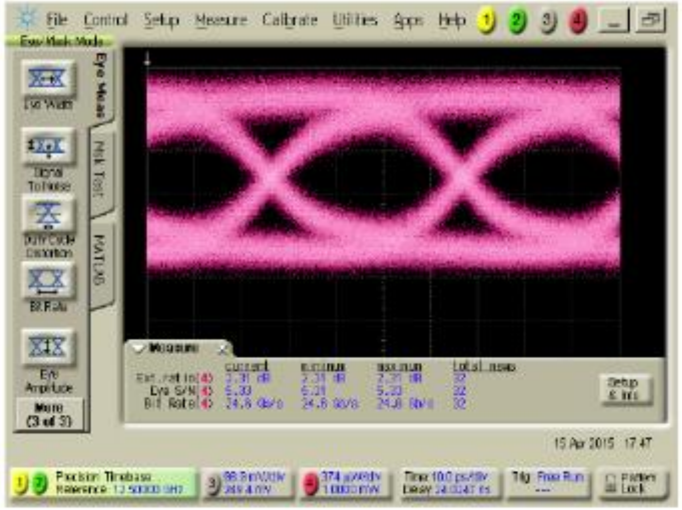
- travelling wave modulator
- ring resonator modulator





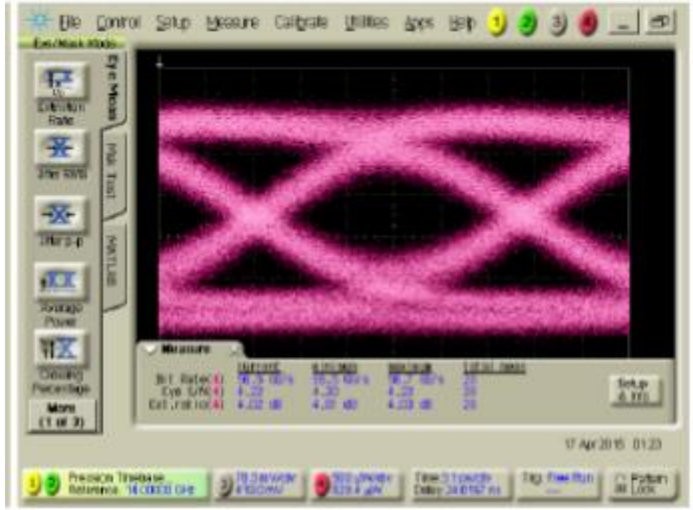
25Gb/s, 1Vpp

Vbias= -0.2V, ER = 2.3dB, Q = 5.3, Opt. Power=13dbm, 1560nm, PRBS=2e31-1

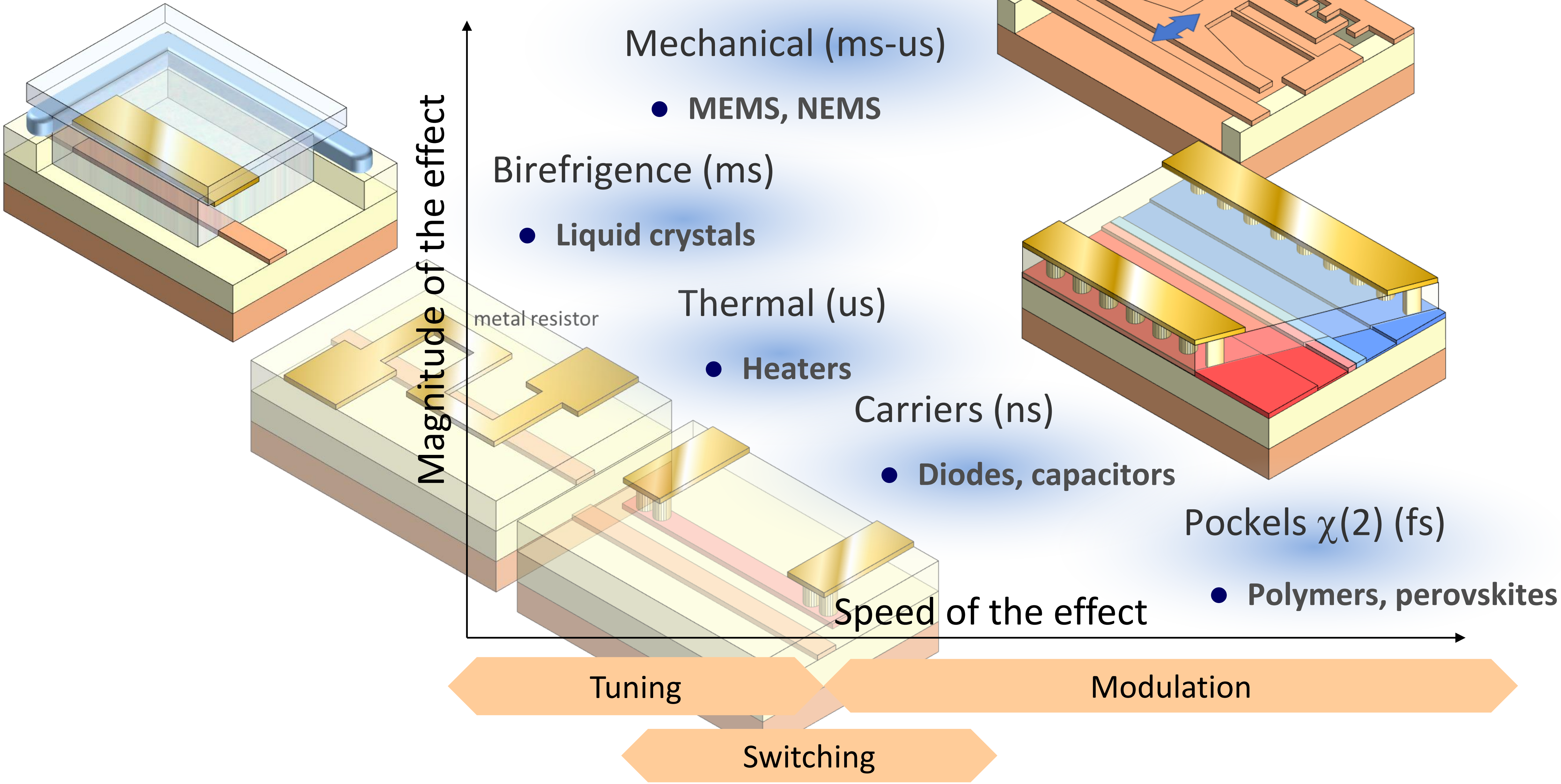


56Gb/s, 2.5Vpp

Vbias=-0.75V, ER=4dB, Q=4.2, PRBS=2e31-1



EFFECT MAGNITUDE VS. SPEED



Liquid Crystal Tuning

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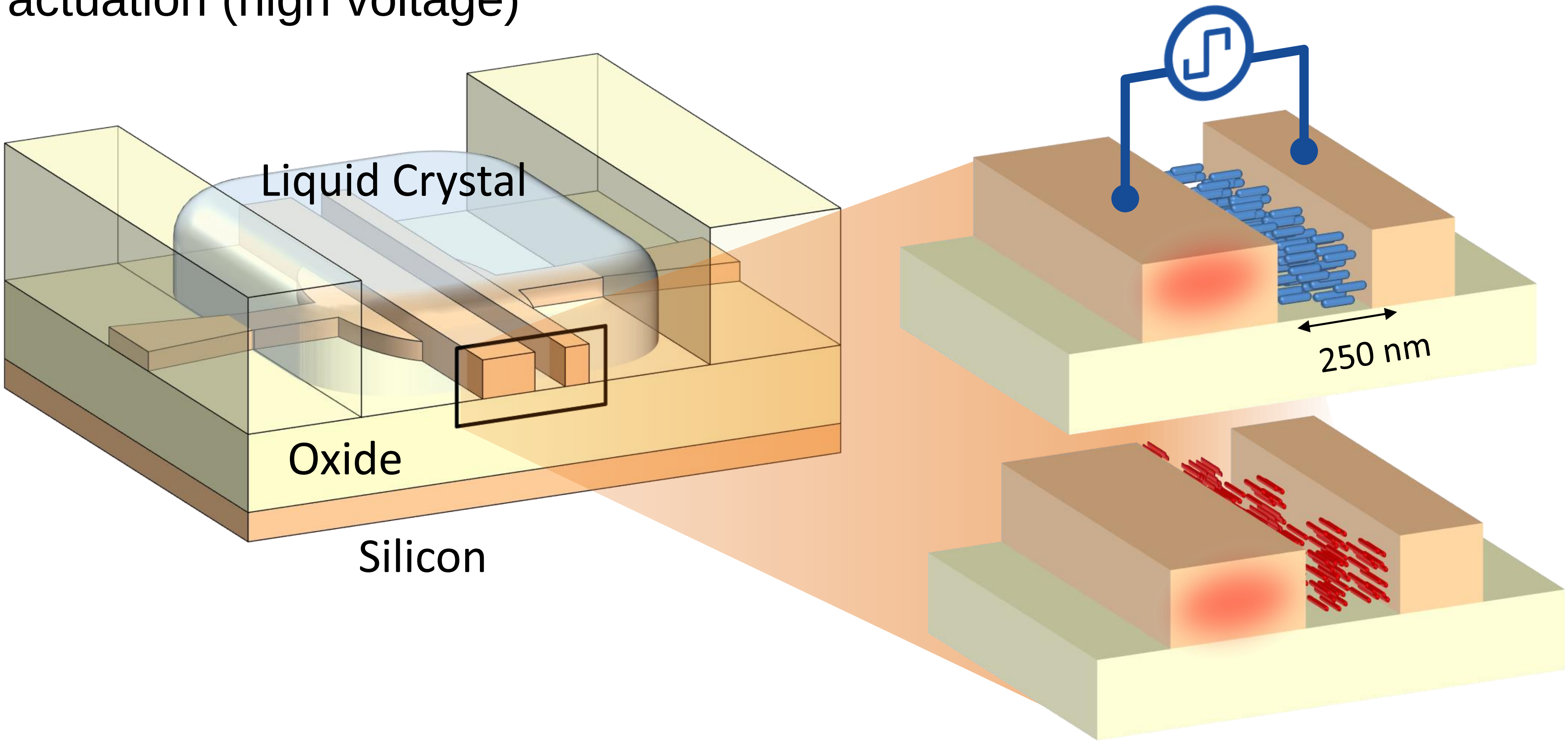
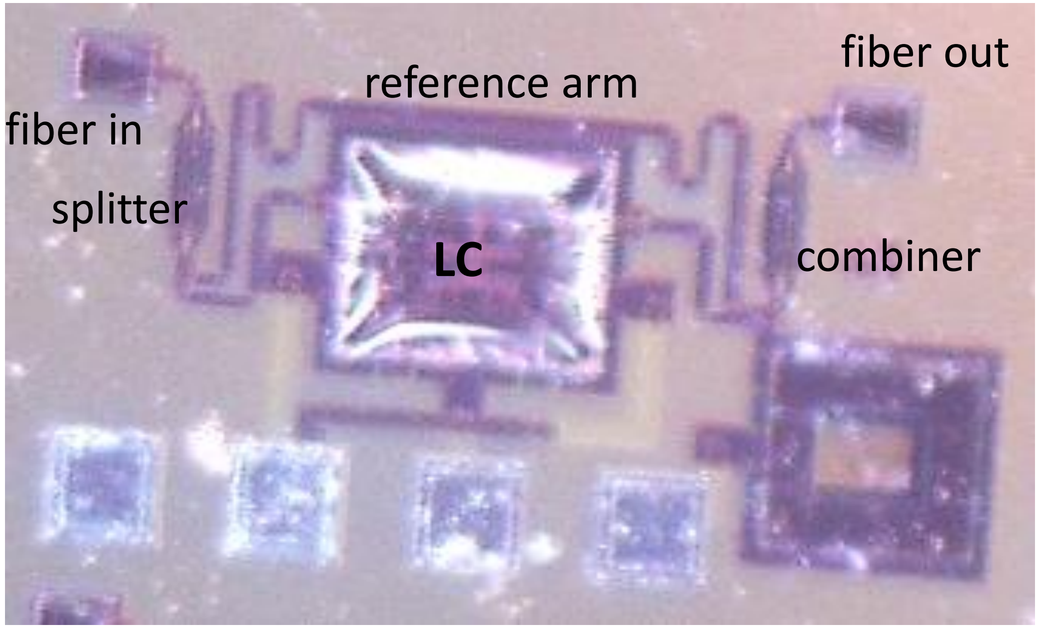
Reorienting molecules

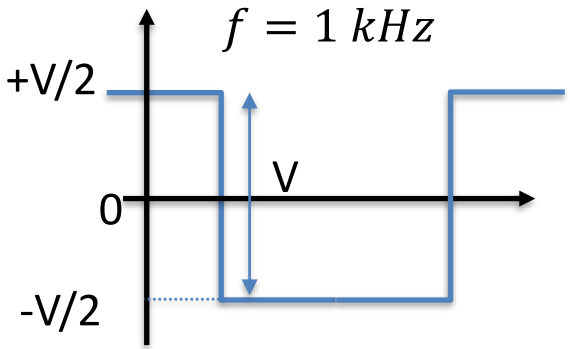
Electrostatic actuation (high voltage)



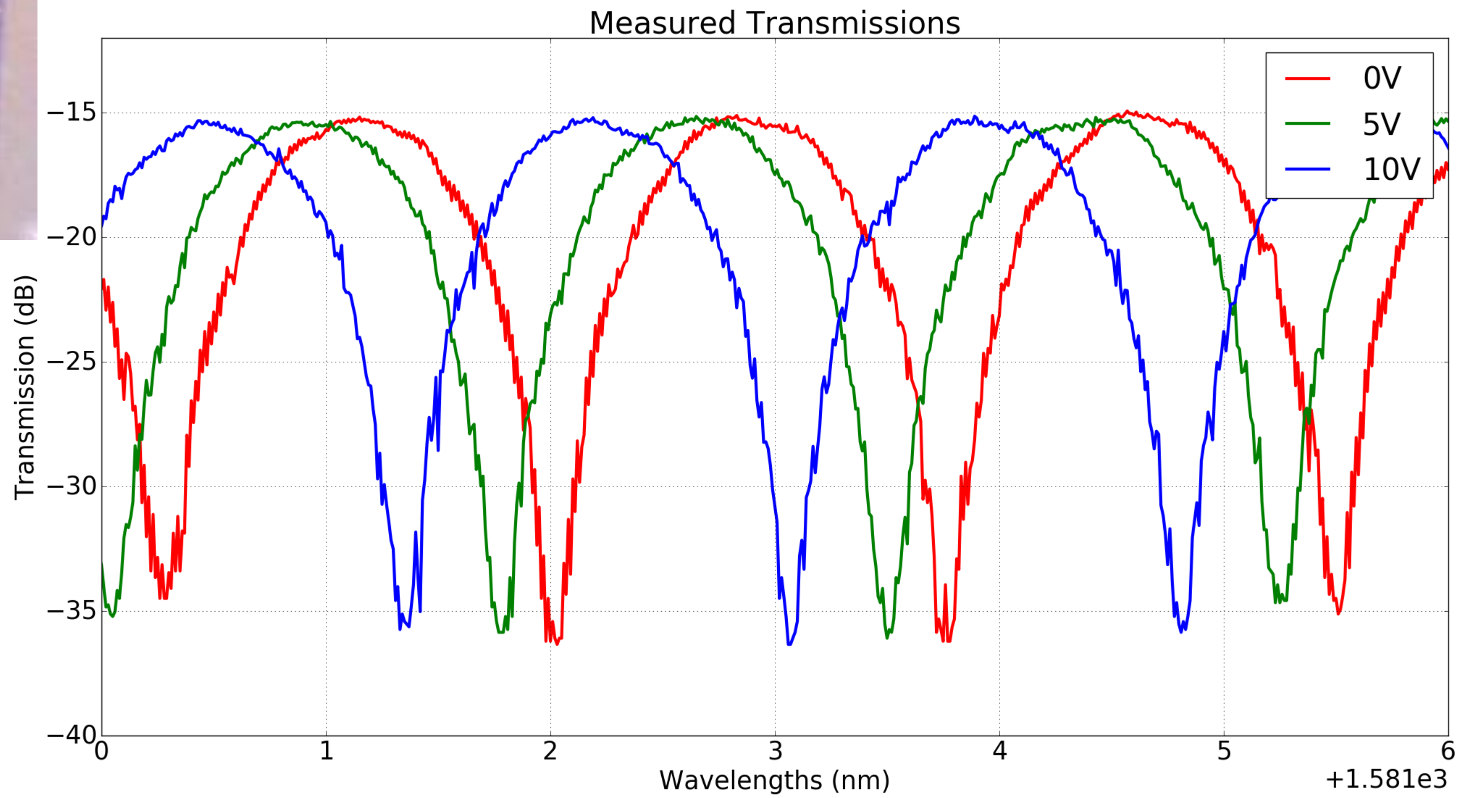
Van Iseghem, ECIO 2020

Liquid Crystal Tuner

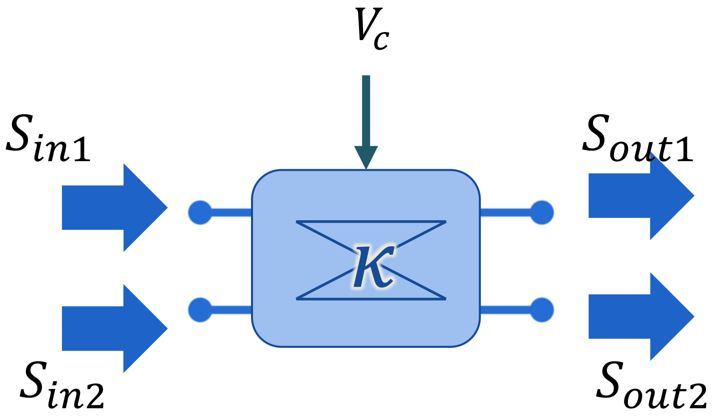




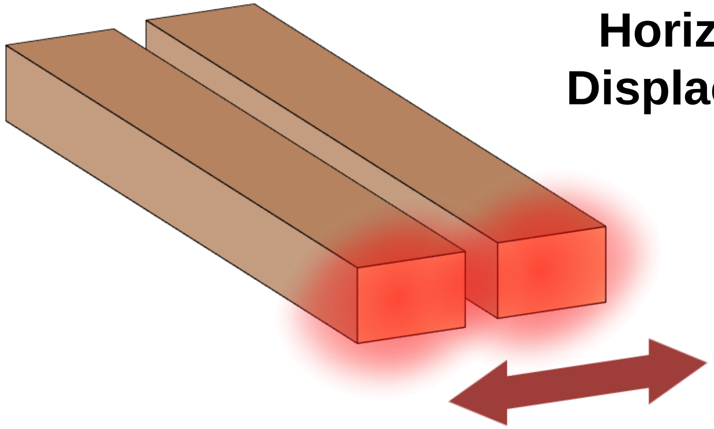
0.8π for 50µm



MECHANICAL TUNABLE WAVEGUIDE COUPLERS



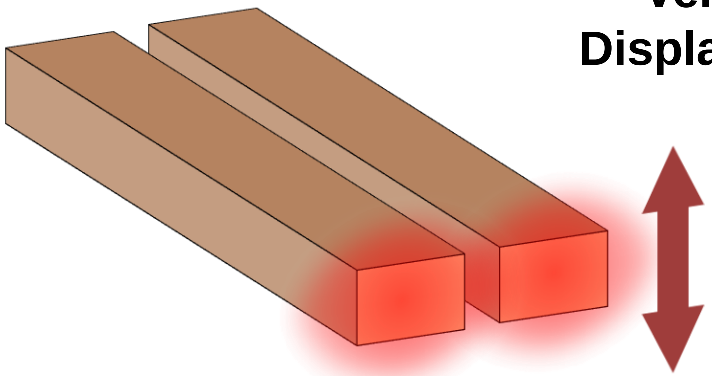
$$S_{out1} = S_{in1}(1-\kappa) + S_{in2}\kappa$$
$$S_{out2} = S_{in1}\kappa + S_{in2}(1-\kappa)$$



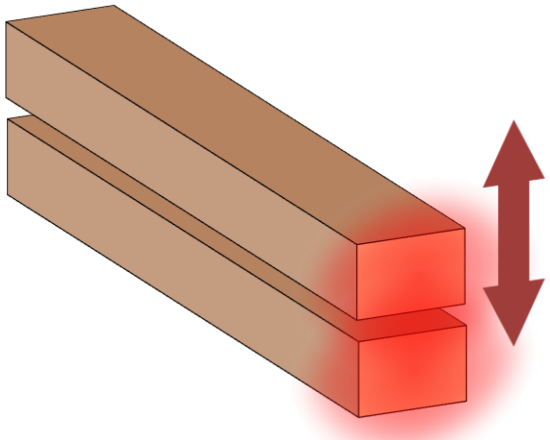
Horizontal Displacement

Single Layer

Stacked Layers

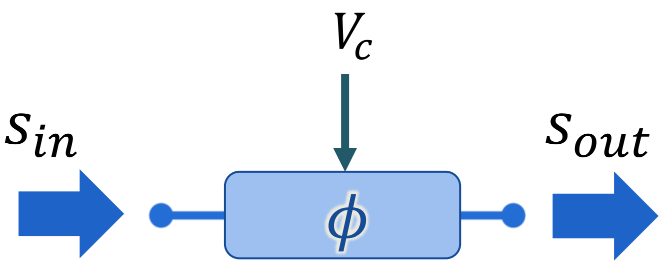


Vertical Displacement



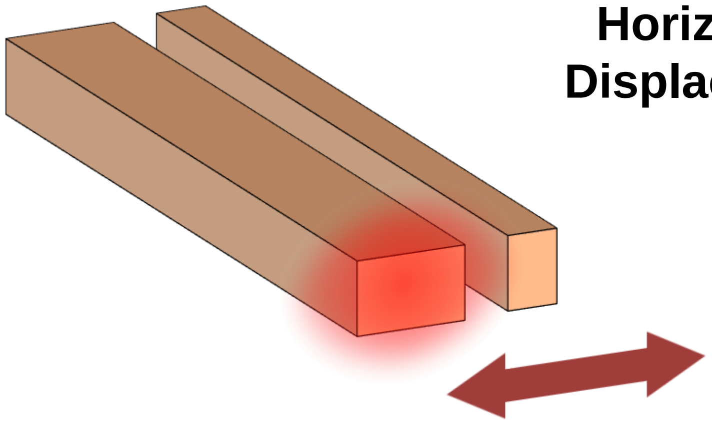
Errando-Herranz, JSTQE 2019

MECHANICAL OPTICAL PHASE SHIFTERS



$$s_{out} = s_{in}.\, e^{j\Delta\phi(V_c)}$$

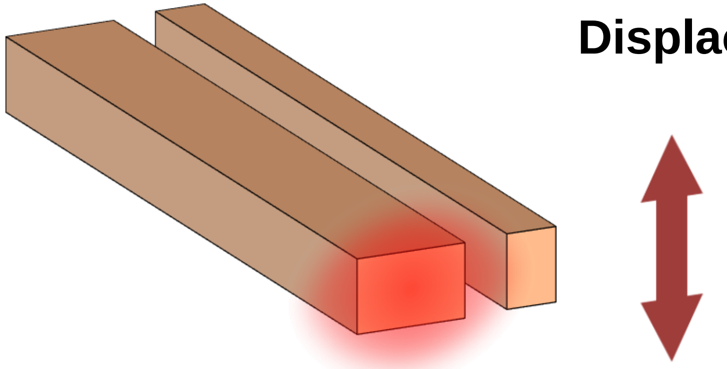
Horizontal Displacement

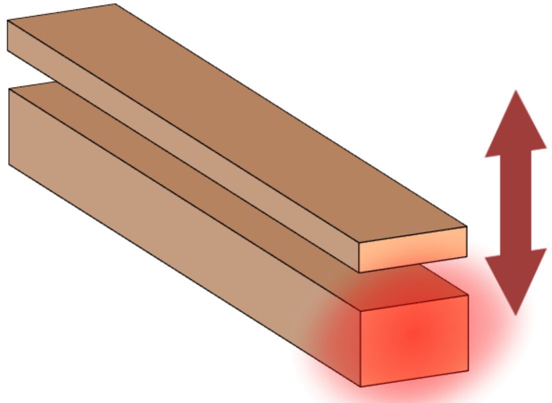


Single Layer

Stacked Layers

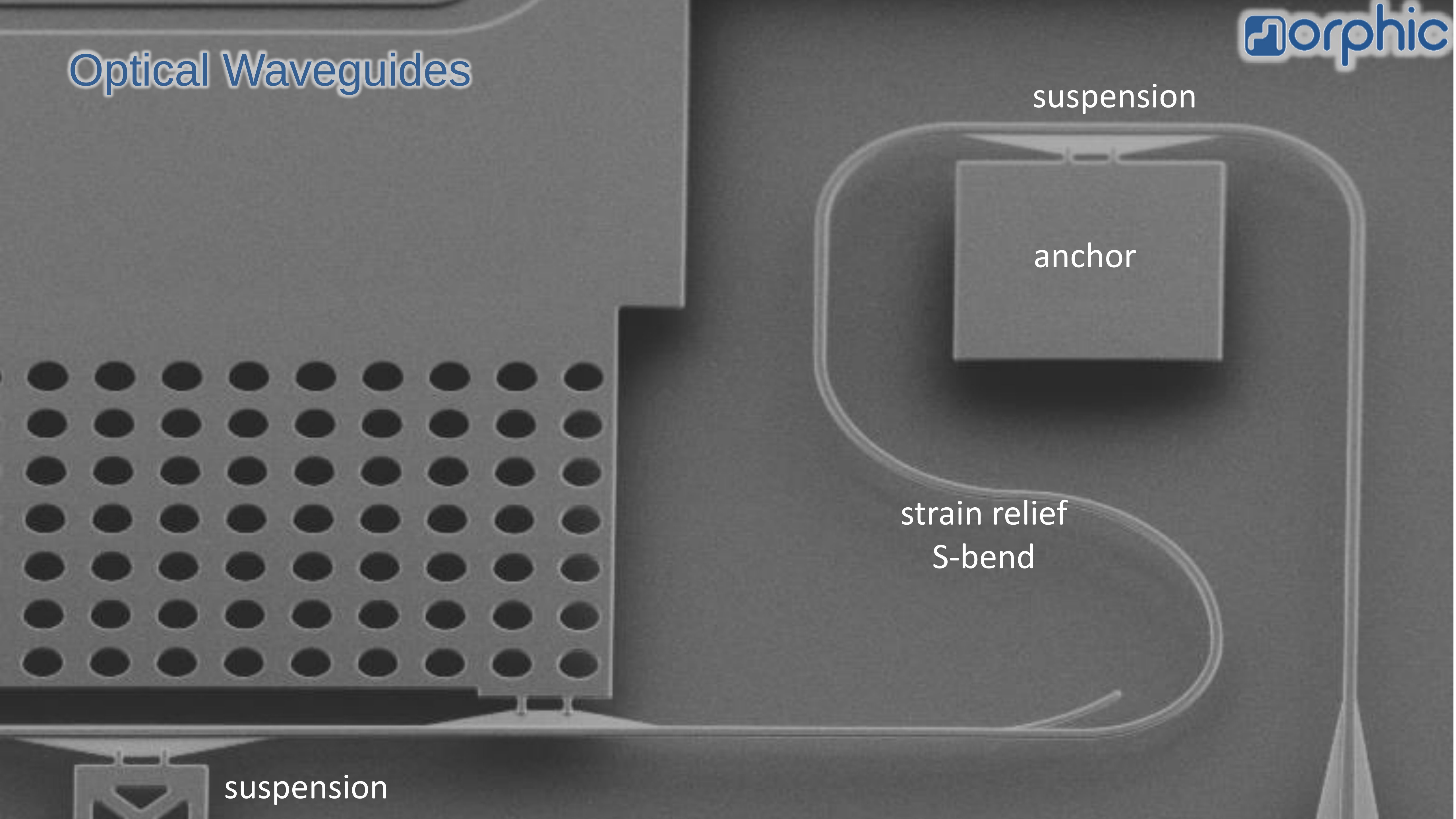
Vertical Displacement



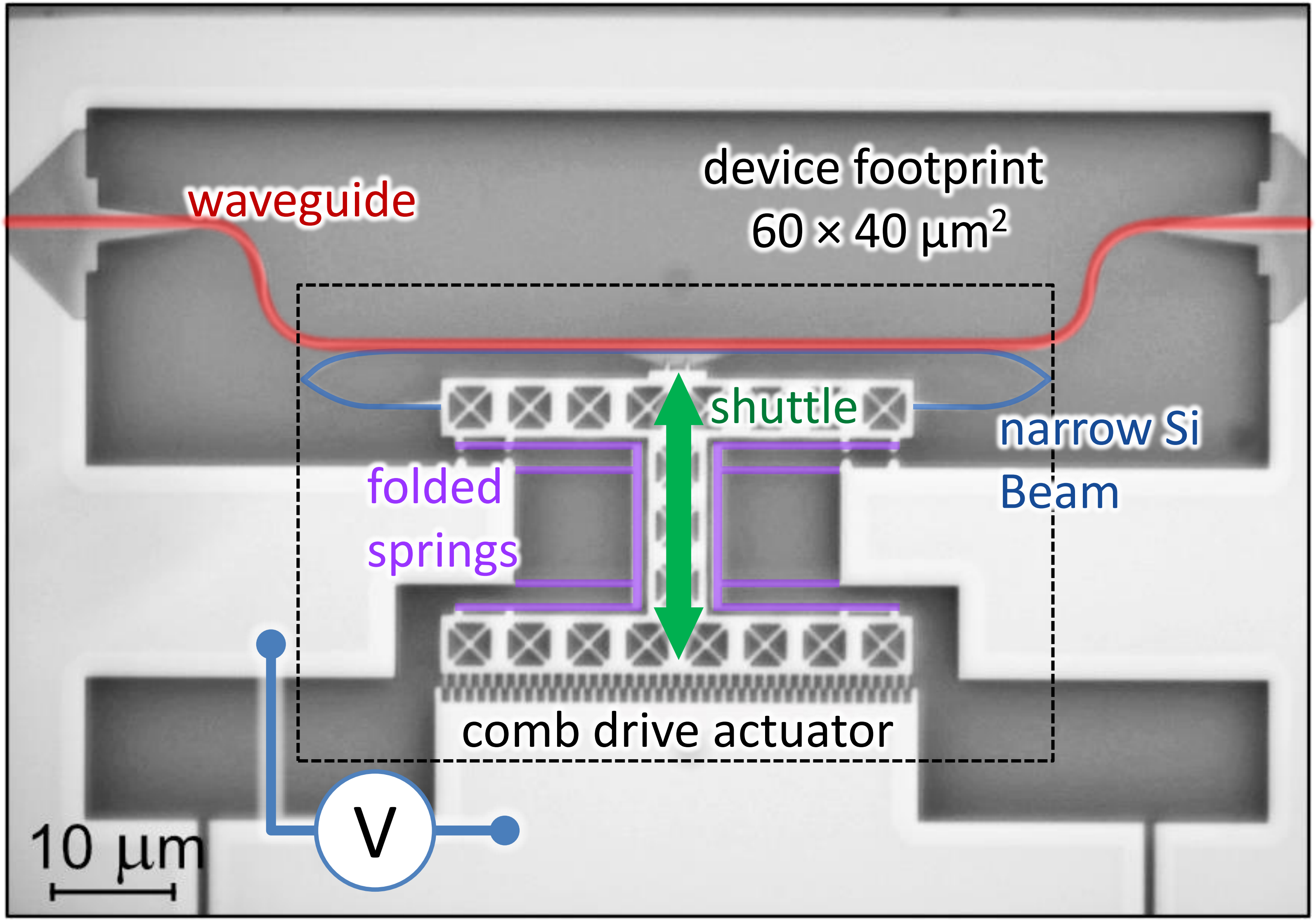


Errando-Herranz, JSTQE 2019

Optical Waveguides



MEMS PHASE SHIFTER



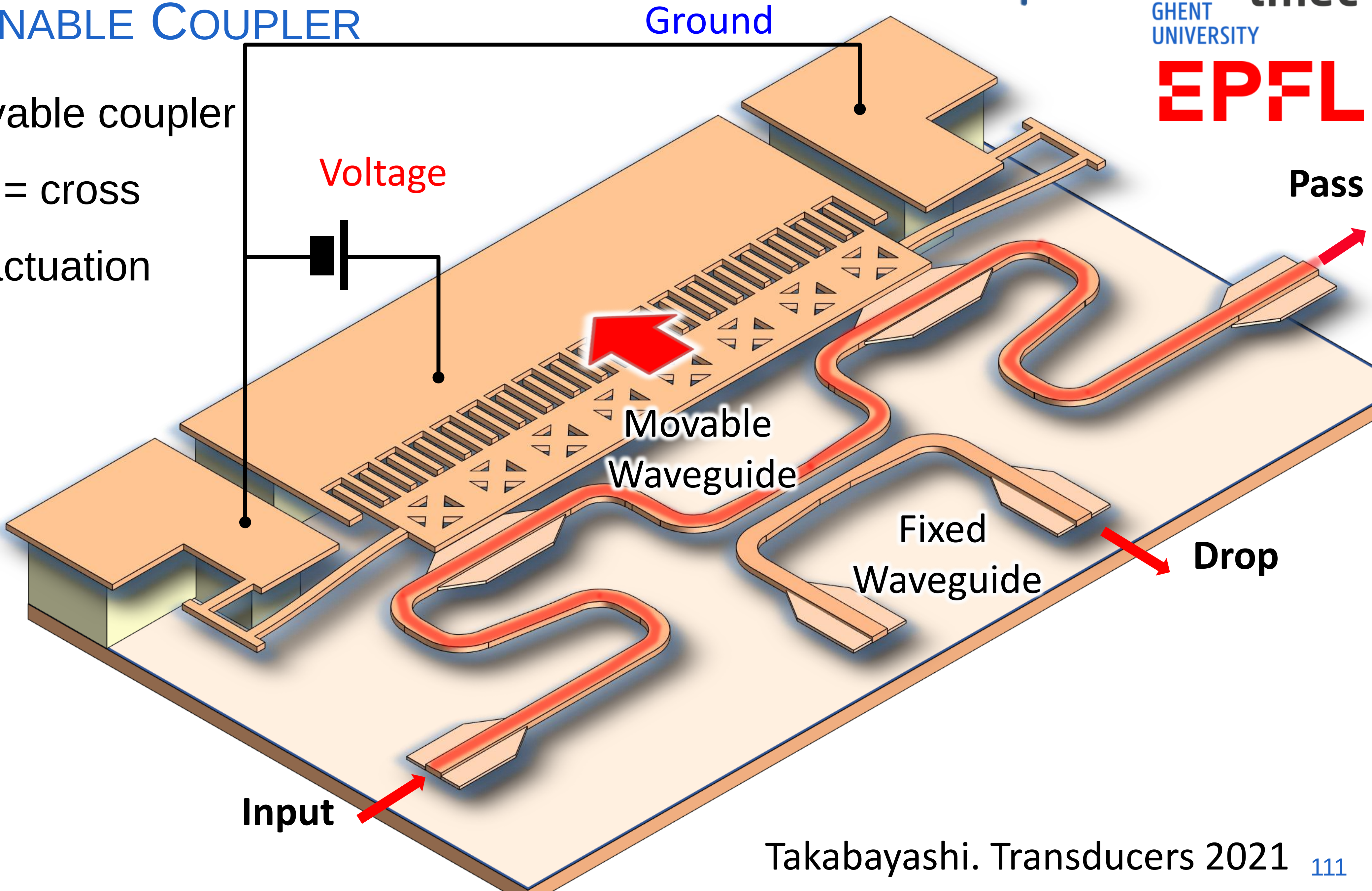
Edinger, CLEO 2021

MEMS Tunable Coupler

In-plane movable coupler

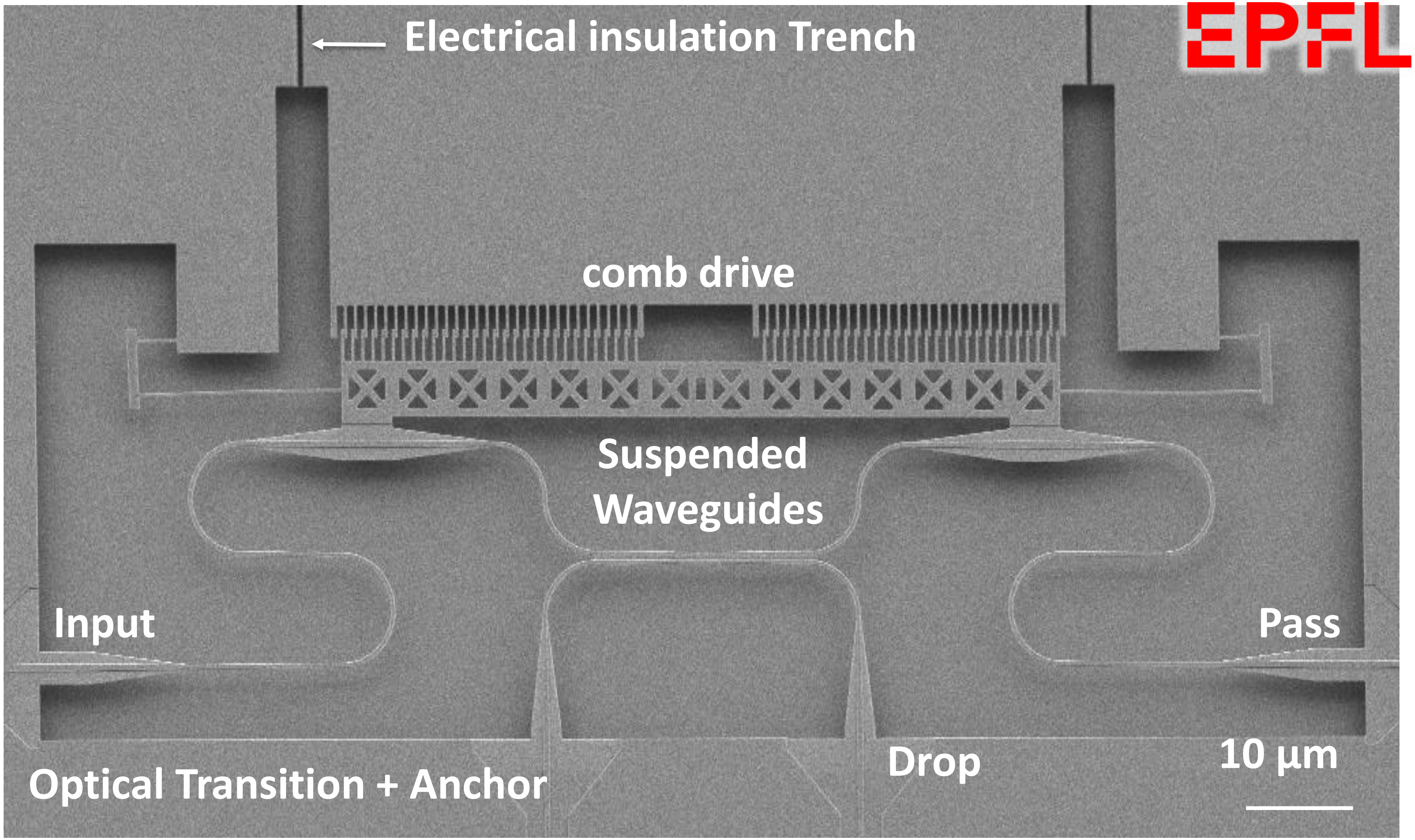
default state = cross

comb drive actuation



Takabayashi. Transducers 2021

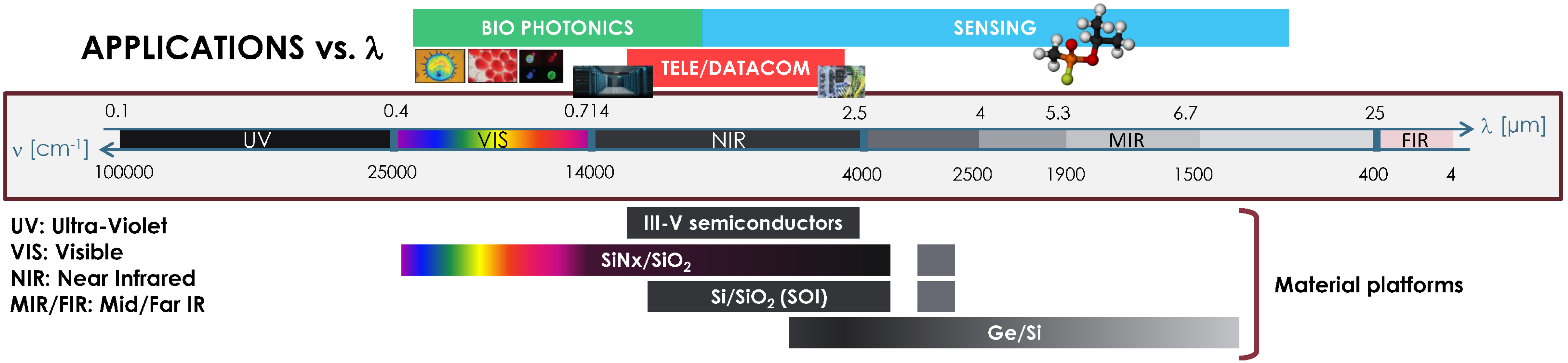
TUNABLE COUPLER



Takabayashi. Transducers 2021

Applications of Photonic Chips

WAVELENGTH RANGE



Telecom: NIR 1250 -1650nm

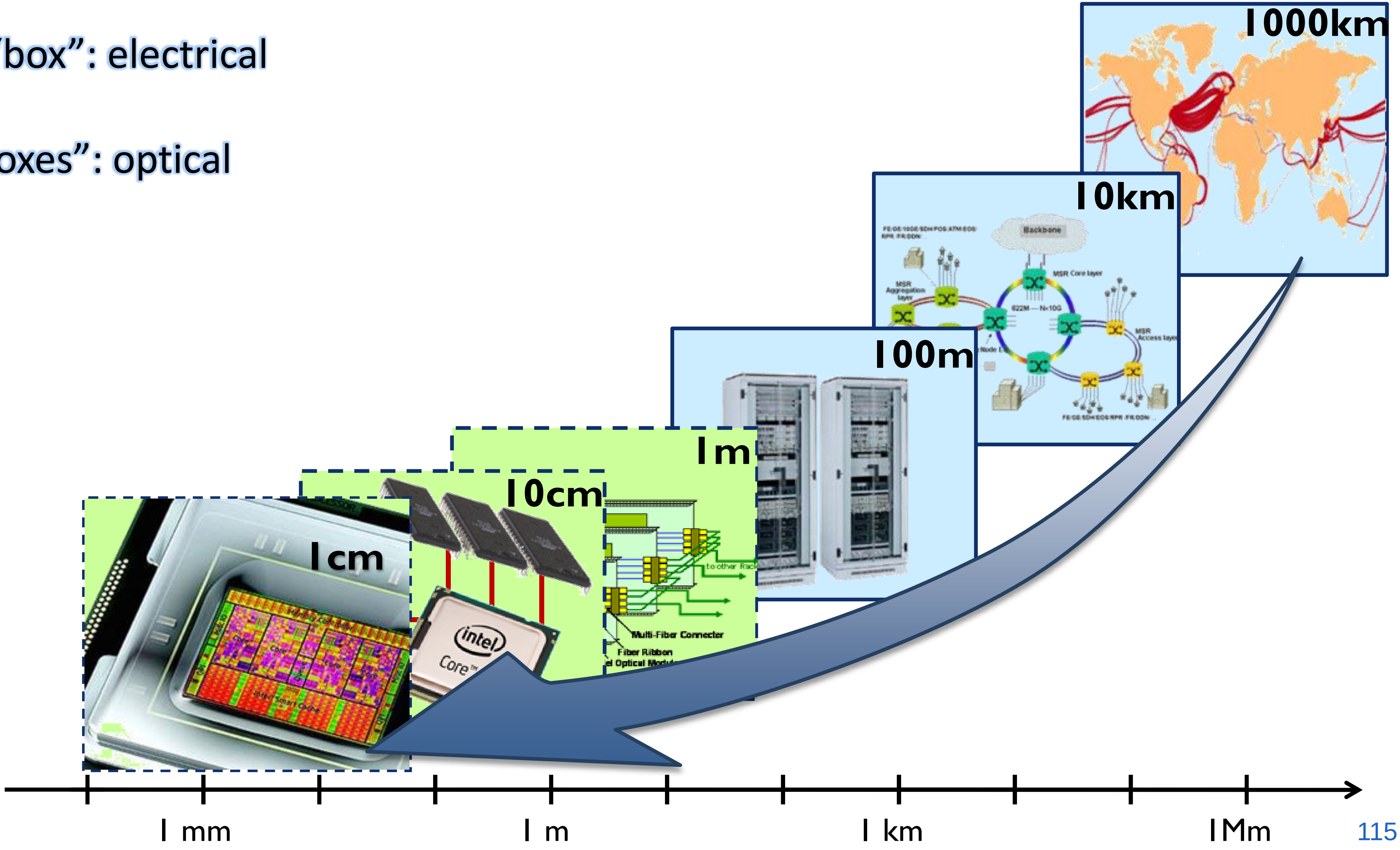
Sensing: 400-10000nm

source: Sensors 2017, 17(9), 2088

OPTICAL LINKS: CONNECTING BOXES…

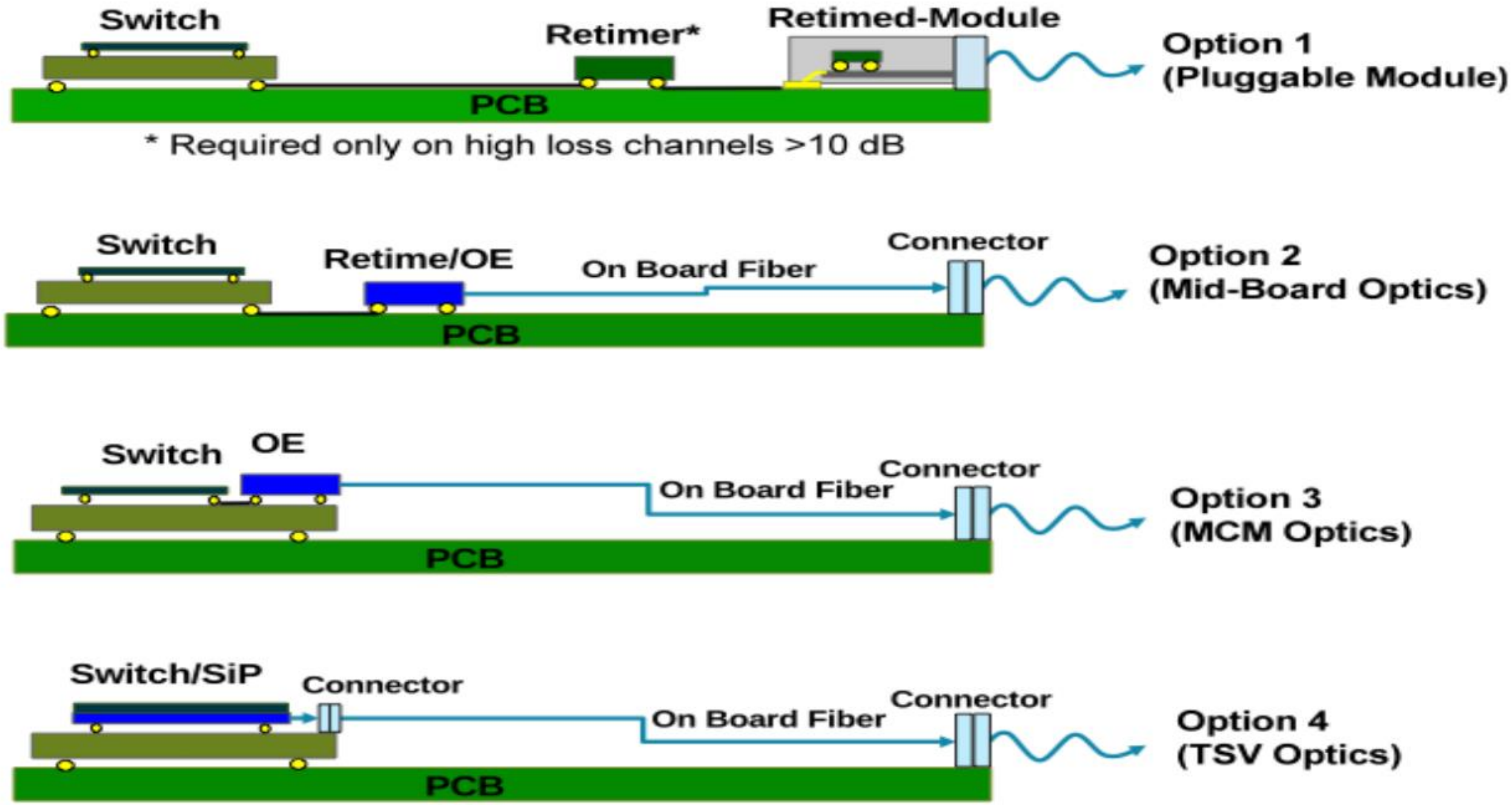
Within the "box": electrical

Between "boxes": optical



ON-BOARD OPTICS

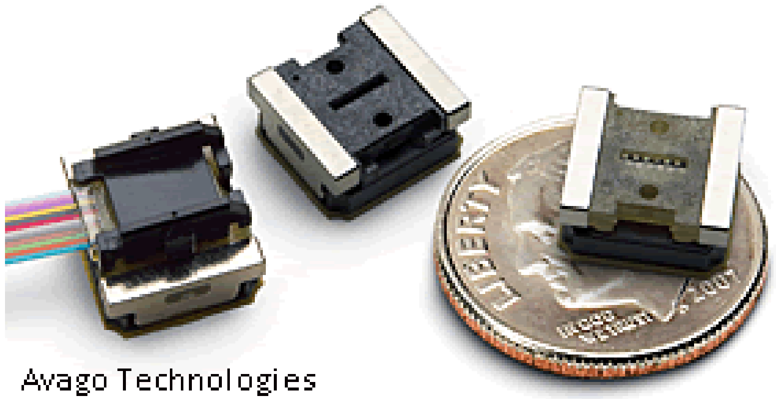
Smaller, cheaper, faster transceivers can come closer to the electronics

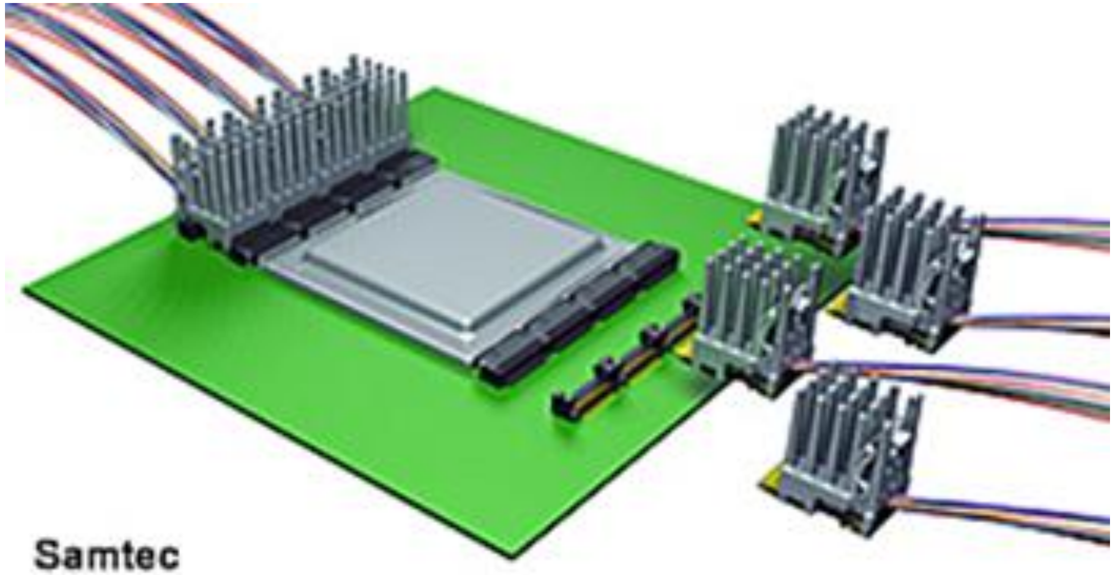


ON-BOARD OPTICS

Replace front-pluggable modules with transceivers on the board

- closer to the electronics, anywhere on the board
- smaller form factor
- Smaller frontplate space (better ventilation)





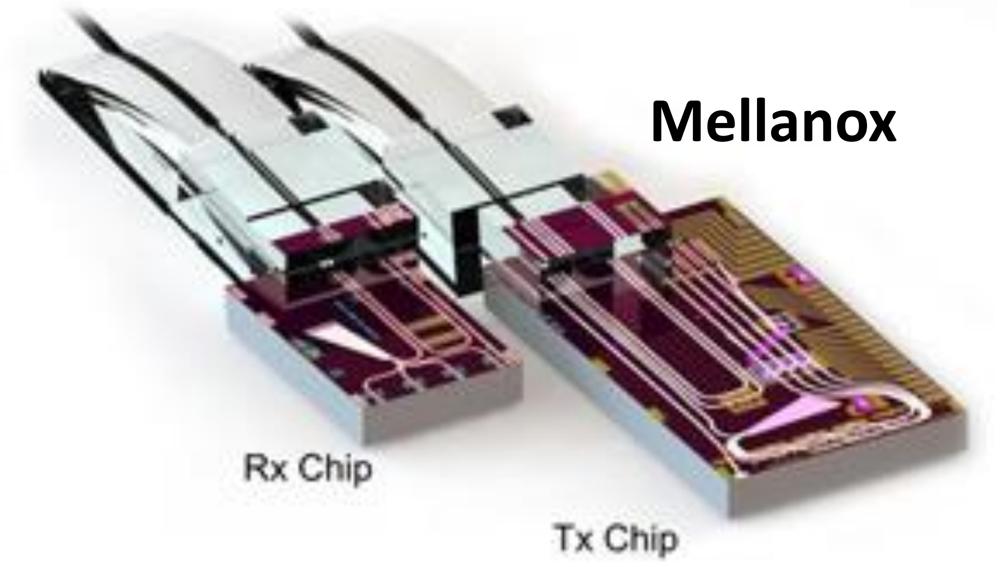
TRANSCEIVERS

Silicon Photonics Transceivers

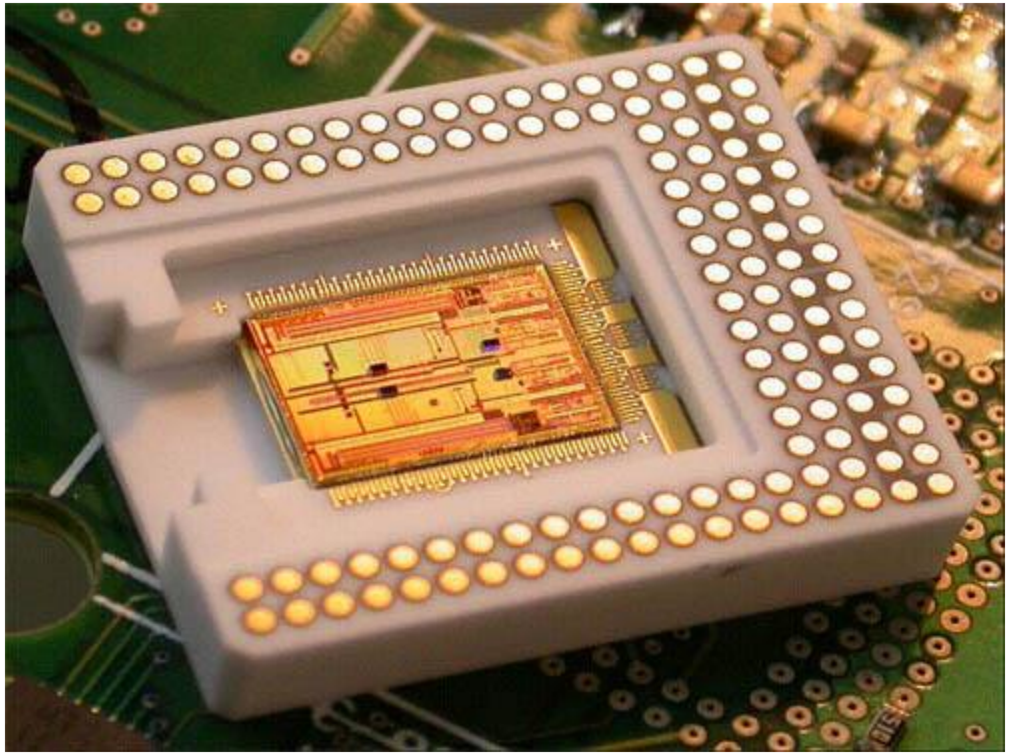
- Targeting Datacenter Applications
- Compatible with single-mode fiber
- Enabling on-board optics

Simplest implementation

- Single wavelength
- Multiple fibers (4×25G, 8×50G)



Mellanox



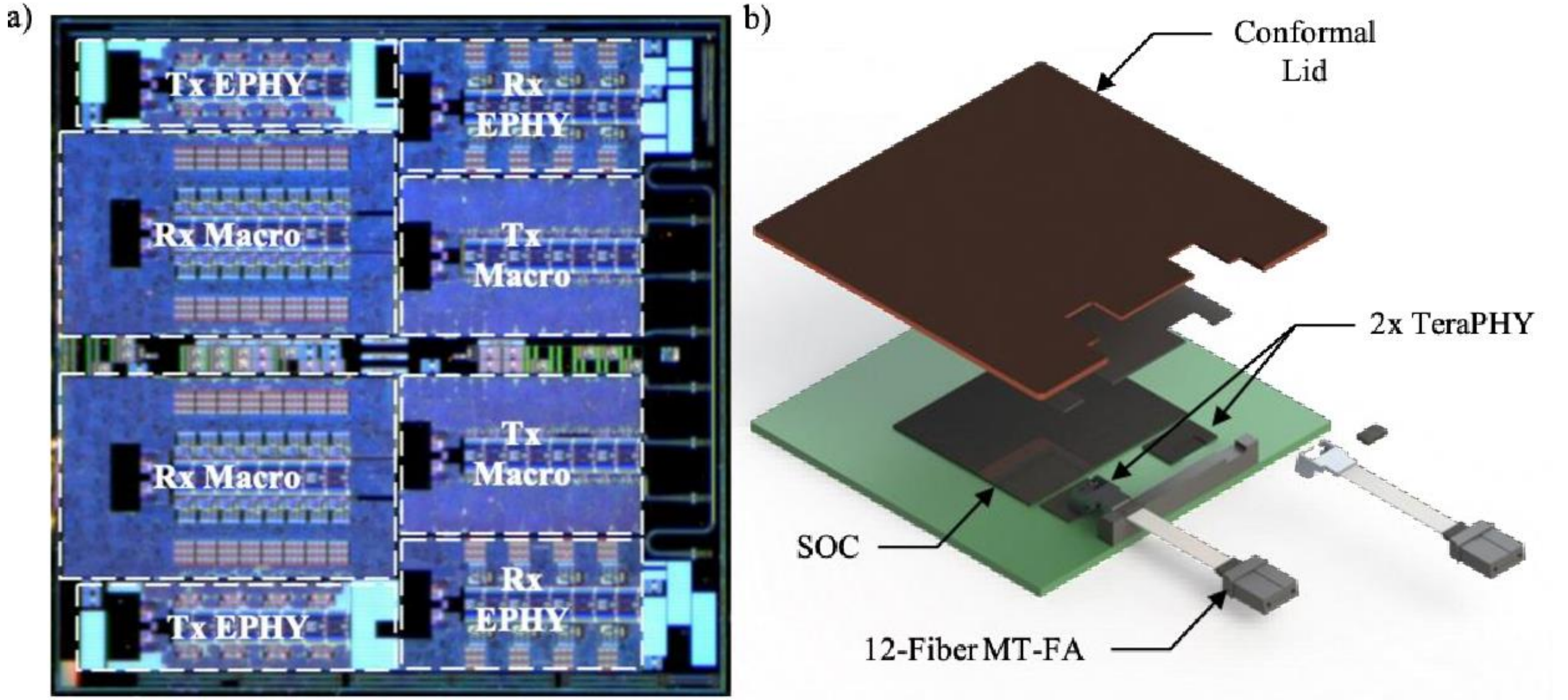
Luxtera

PACKAGE-LEVEL OPTICAL COMMUNICATION

Example: TeraPHY (Ayar Labs – INTEL)

Tx/Rx Chiplets next to CPU/GPU/Memory within the same package

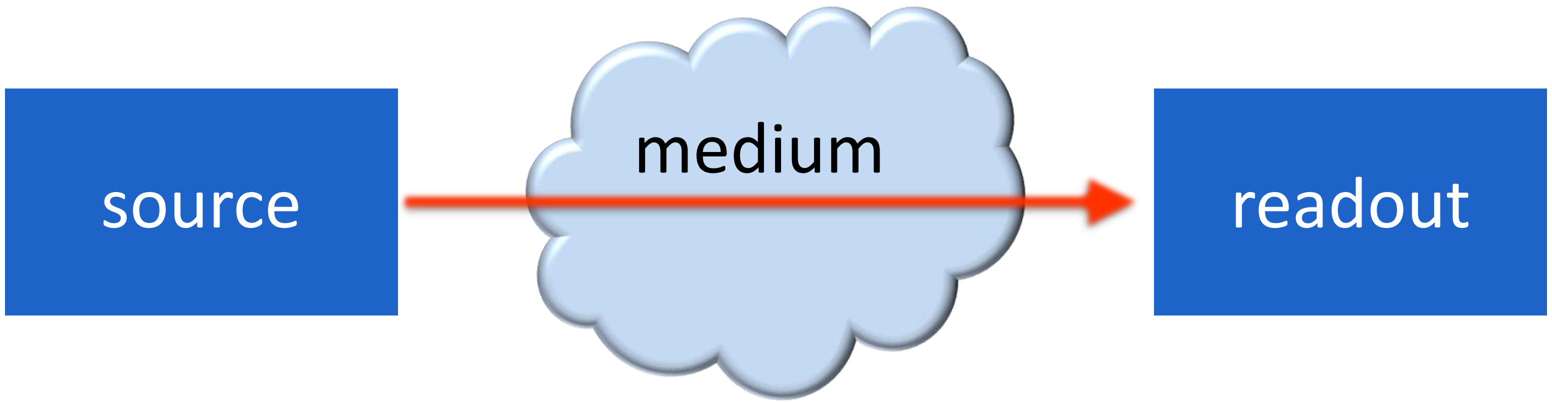
Made in silicon photonics with monolithic electronics



OPTICAL SENSOR

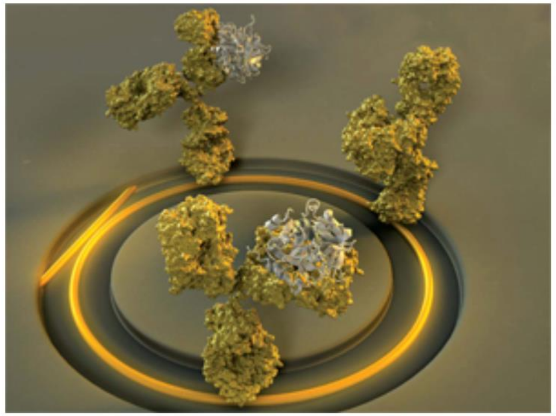
Measure the change of optical signal as it passes through a medium

- Intensity
- Phase (very sensitive!)
- Wavelength (spectrum)

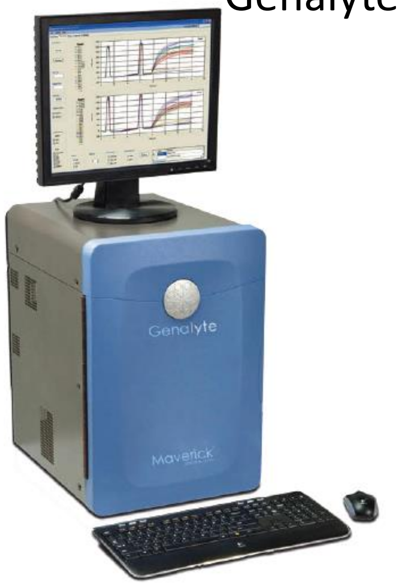


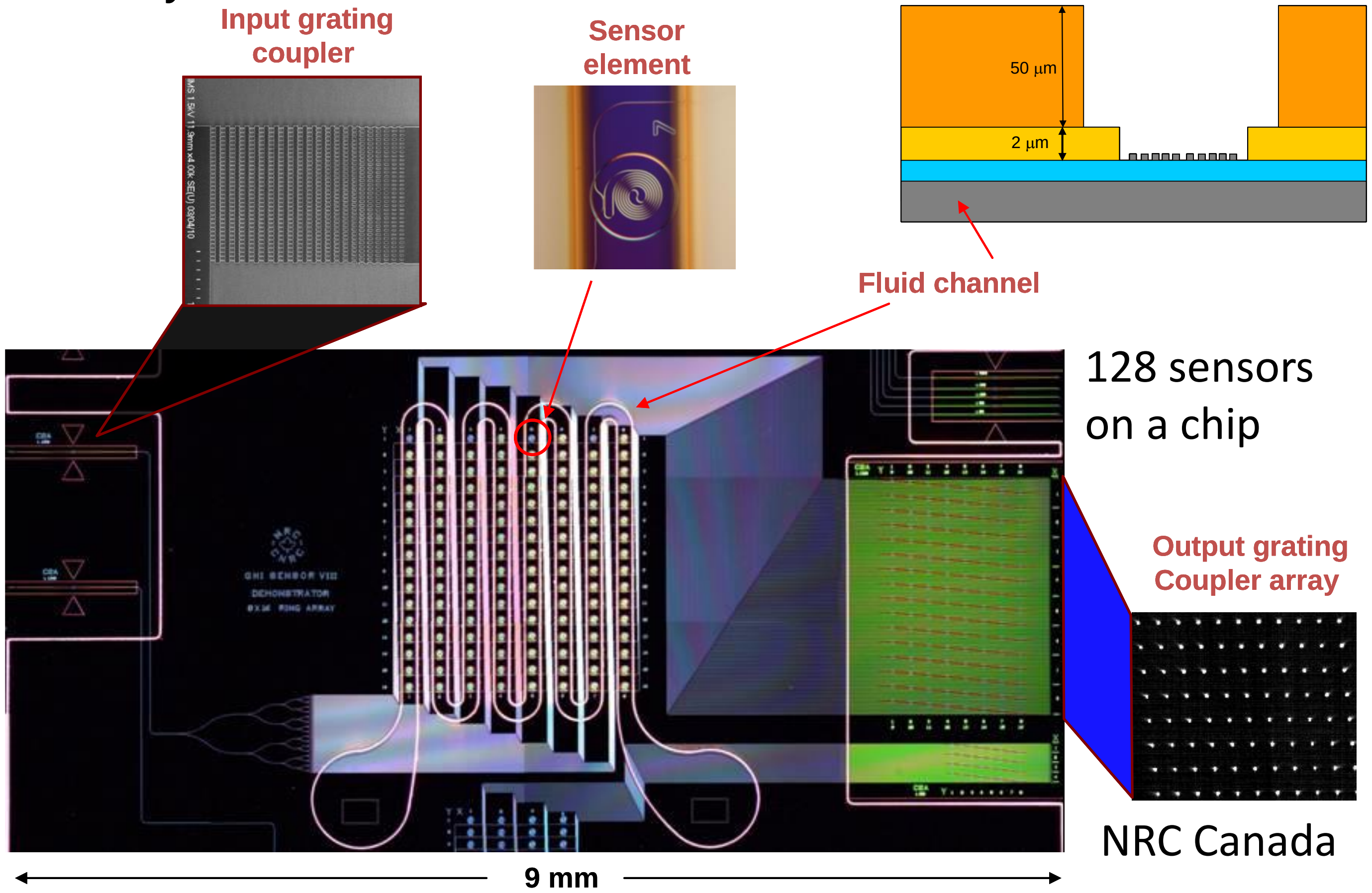
(BIO)MOLECULE SENSORS

- Silicon photonics: cheap disposable sensor
- Needs transducer to translate the presence of particular molecules into a refractive index change
- Mostly work on the chemistry / material science side



Genalyte

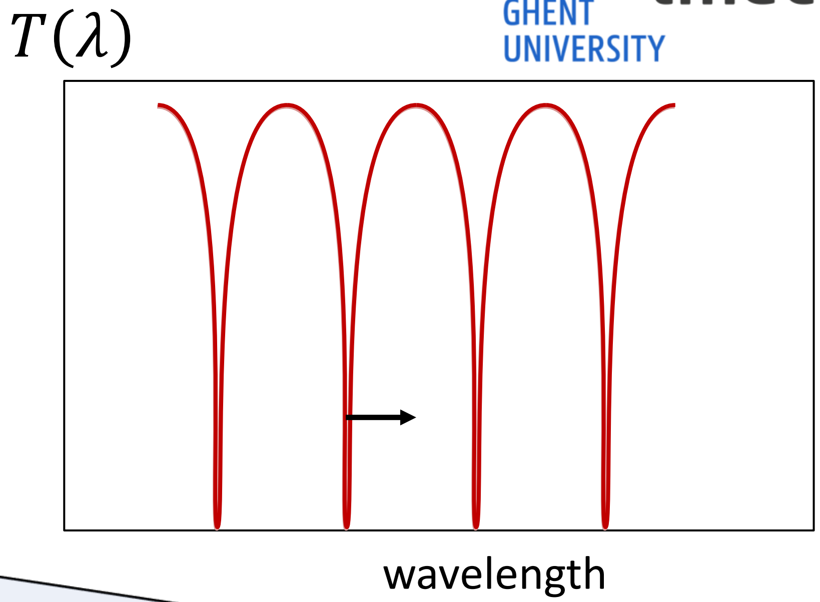


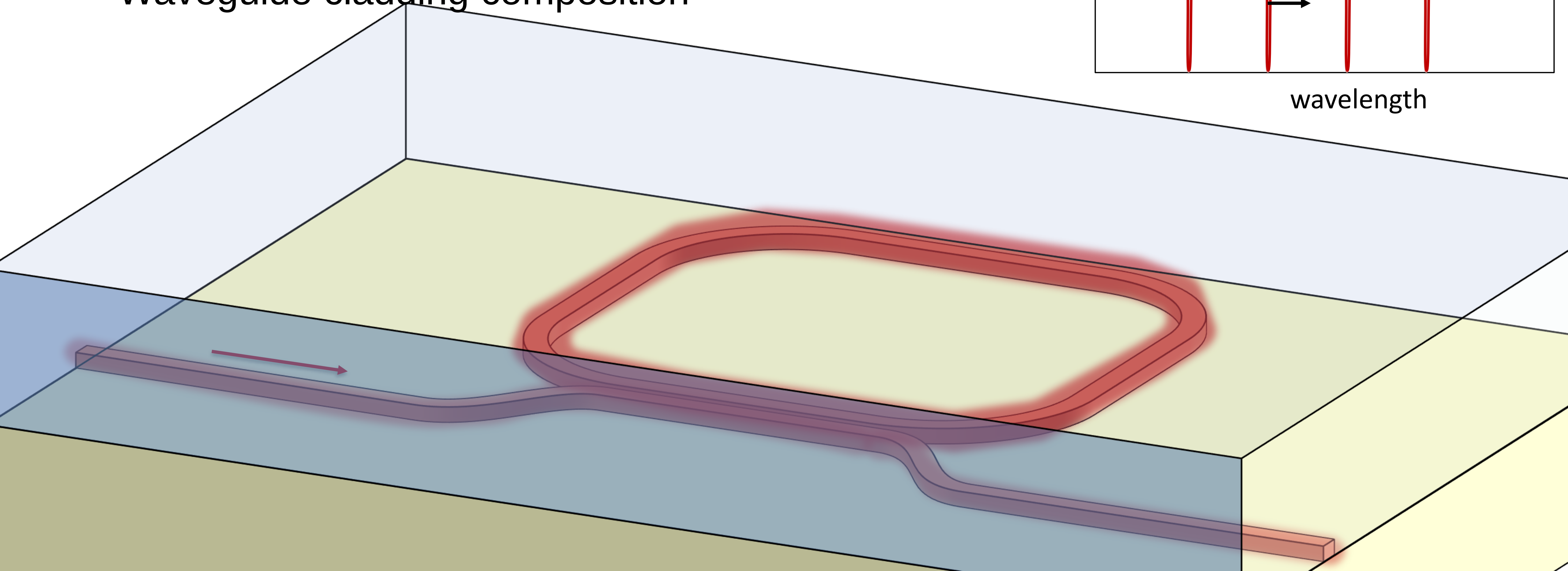


Ring Resonator Sensors

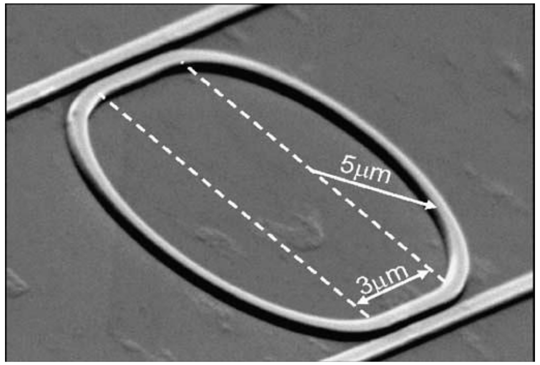
Resonance wavelength shift: $$\frac{\Delta\lambda_{res}}{\lambda} = \frac{\Delta n_{eff}}{n_g}$$

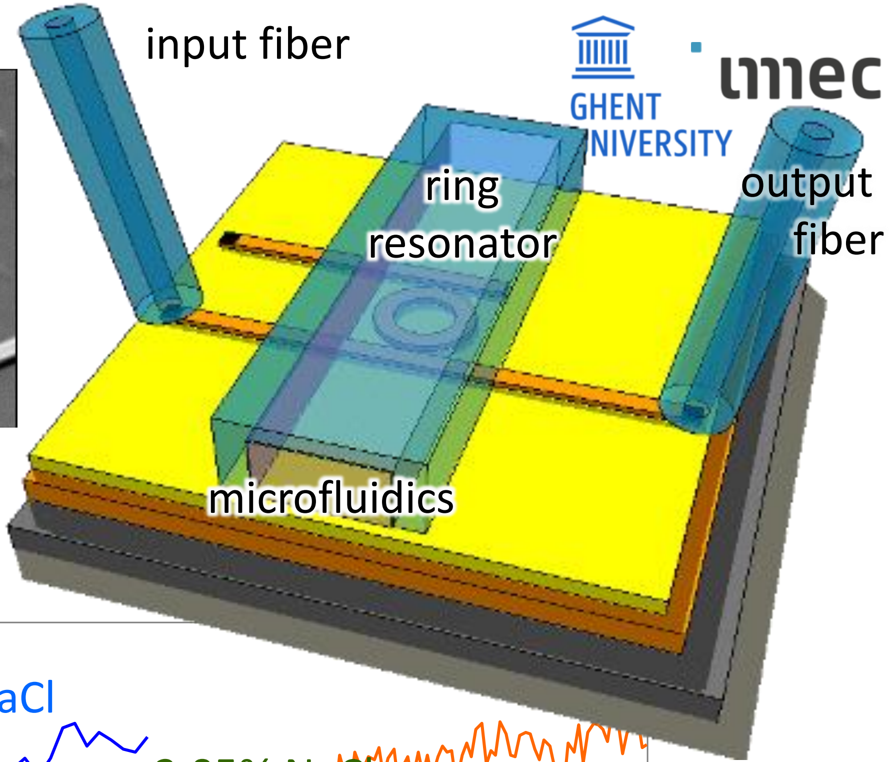
- Temperature, Strain, …
- Waveguide cladding composition





Ring resonator Sensors

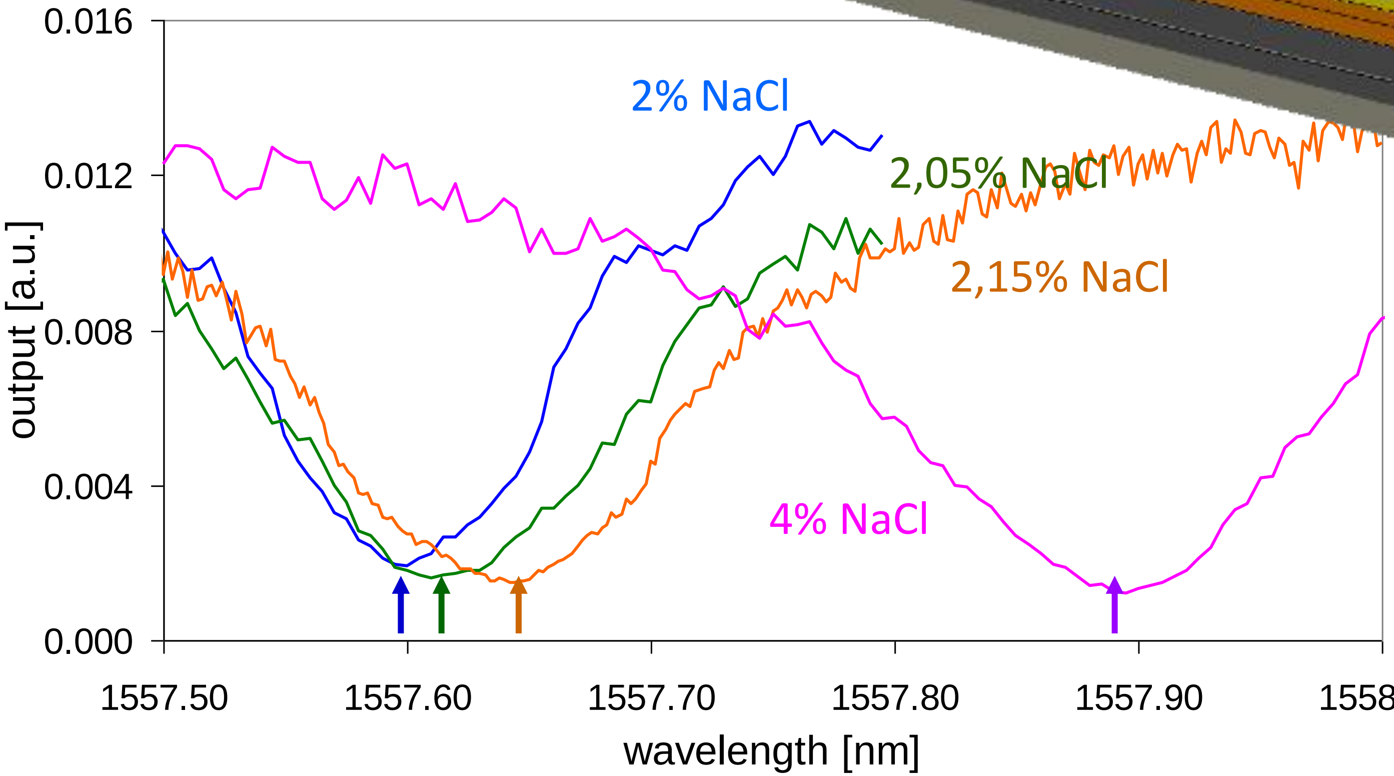




Microfluidic channels with liquid

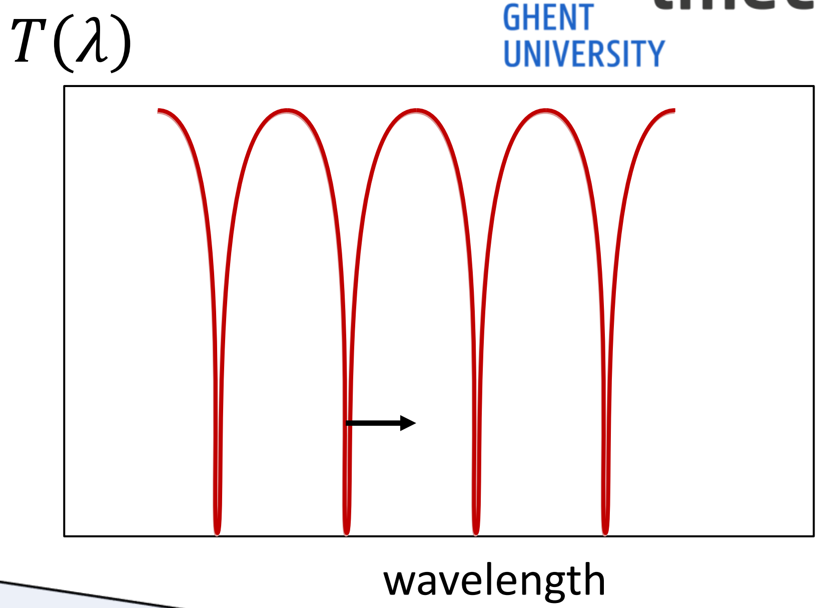
$$\frac{\partial \lambda_{res}}{\partial n_{cladding}} = 86.6 \frac{nm}{RIU}$$

Example: salt concentration



K. De Vos, OpEx 15, p.7610 (2007)

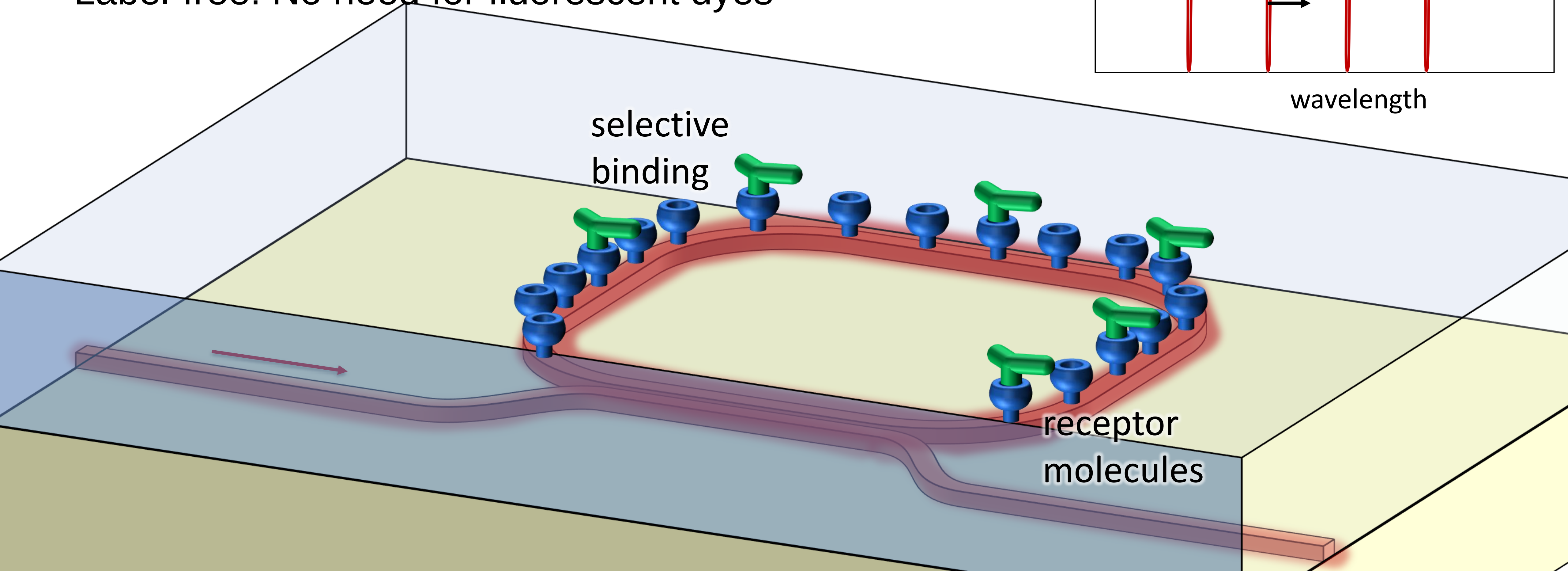
Ring resonator Biosensors



Attach ligand molecules to rings

Only matching molecules will bind and shift resonance

Label-free: No need for fluorescent dyes

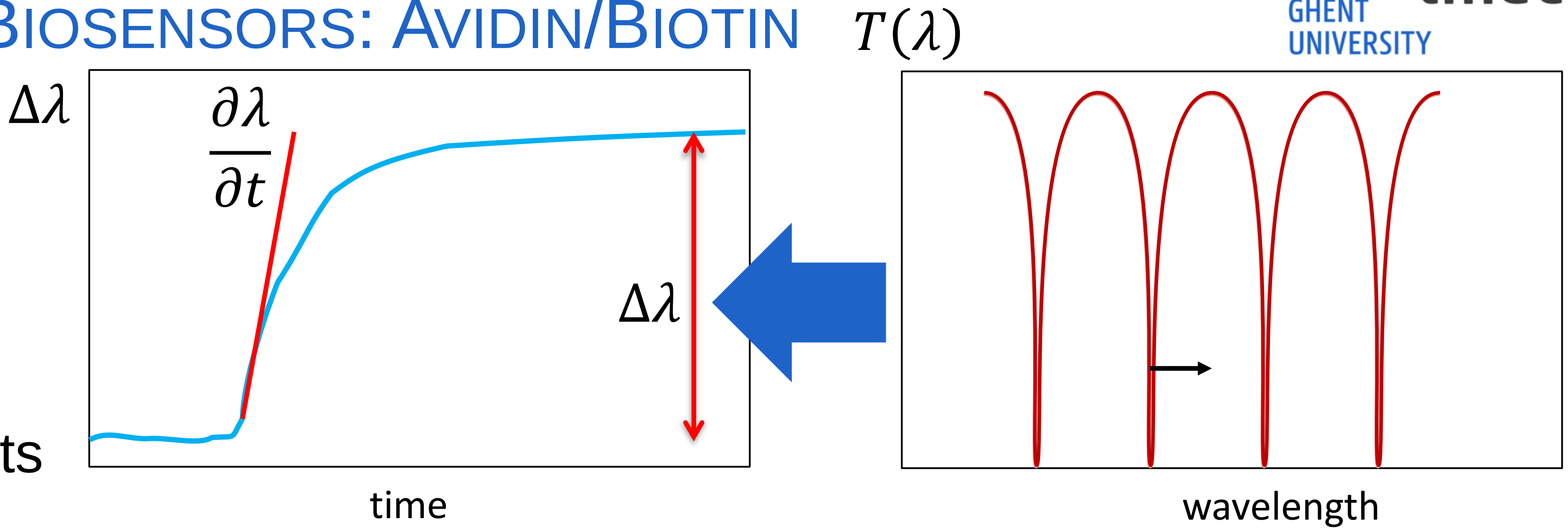


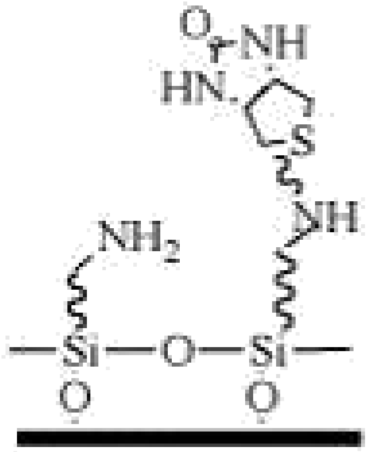
RING RESONATOR BIOSENSORS: AVIDIN/BIOTIN

selective binding

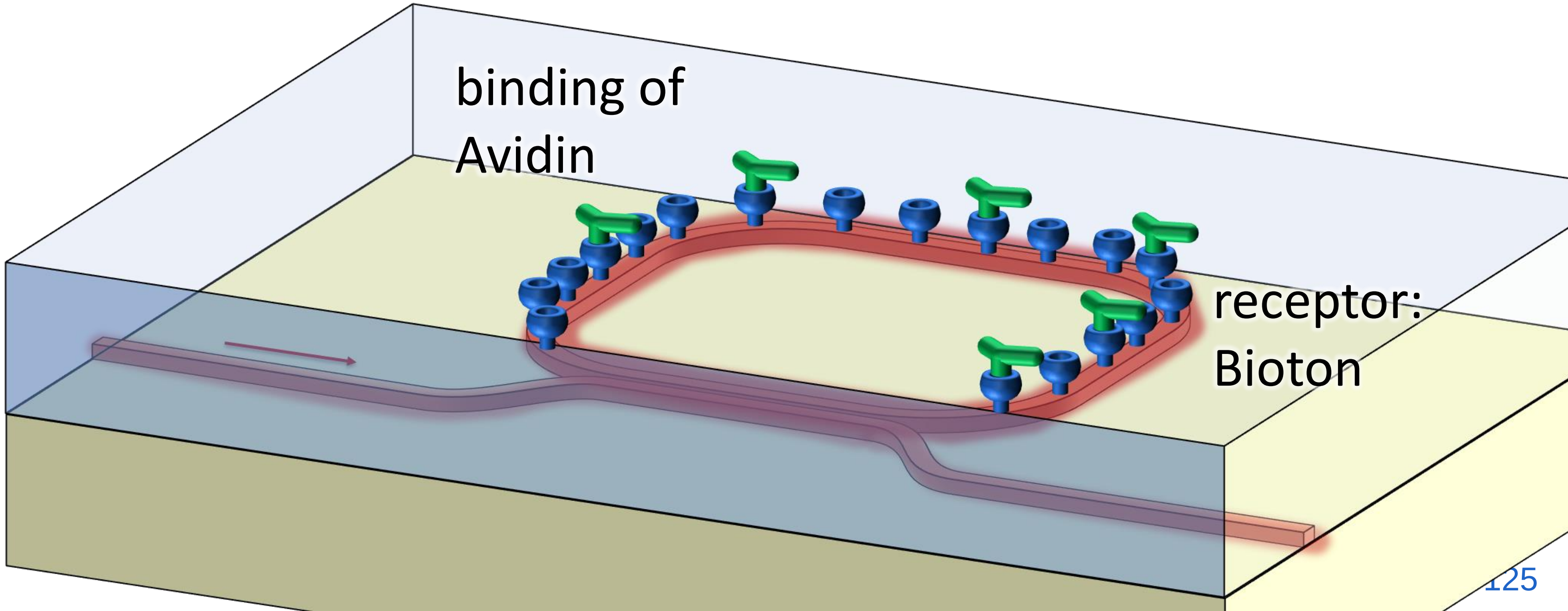
- shift ~ concentration
- rate ~concentration

Ultra-low detection limits



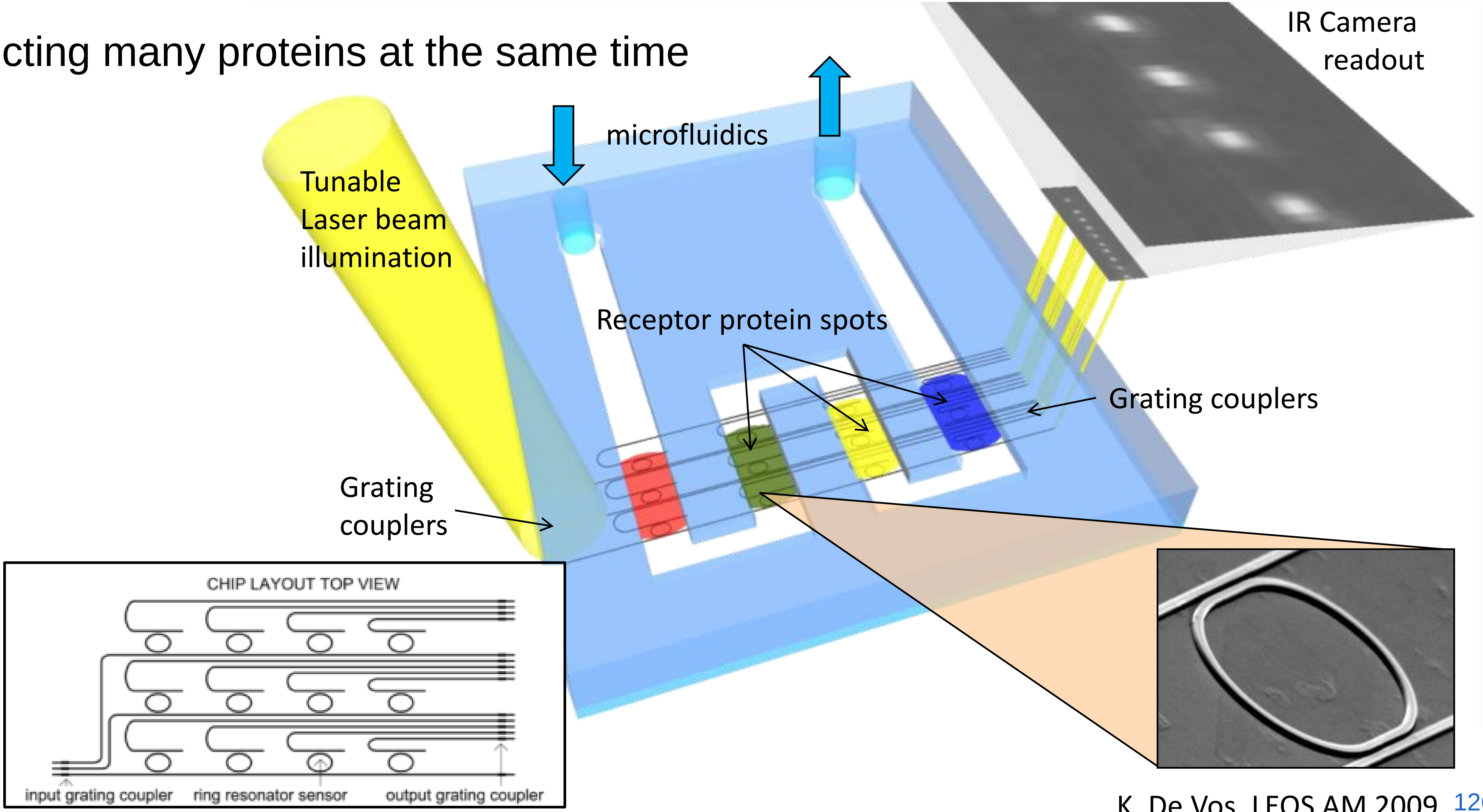


Si-Biotin



Ring Resonator Biosensors: multiplexing

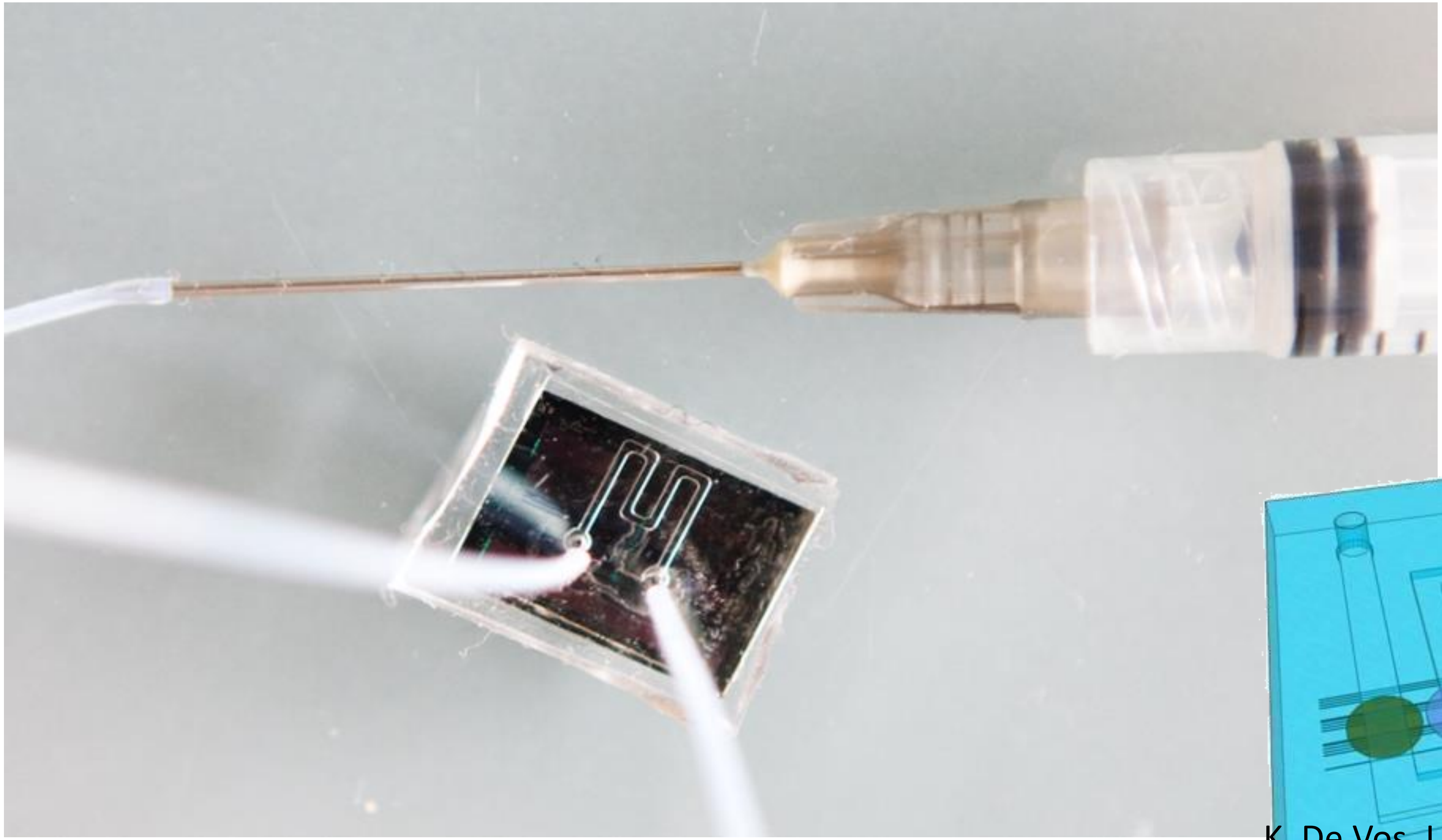
Detecting many proteins at the same time

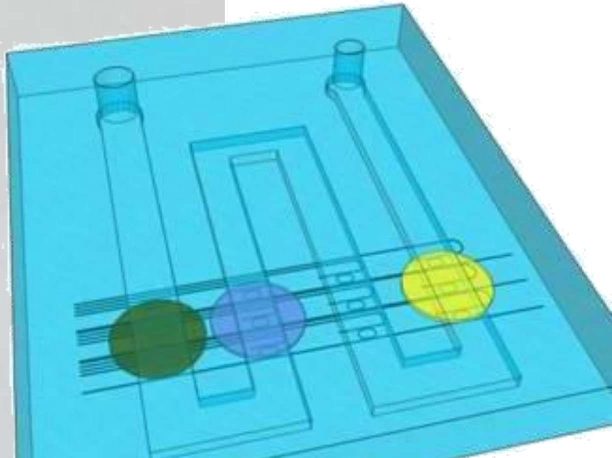


K. De Vos, LEOS AM 2009

RING RESONATOR BIOSENSORS: MULTIPLEXING

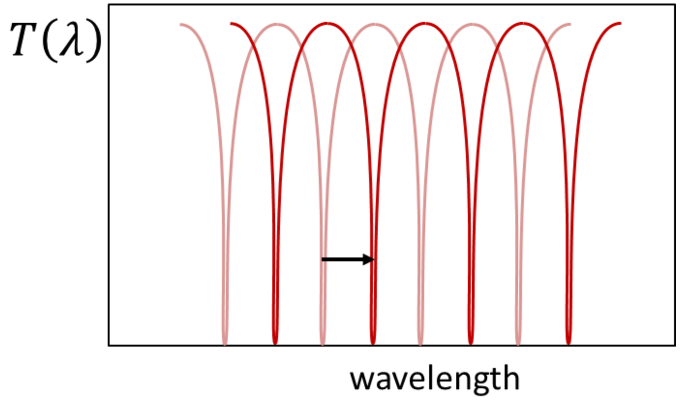
Detecting many proteins at the same time

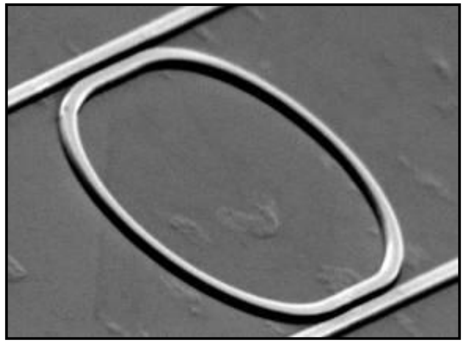


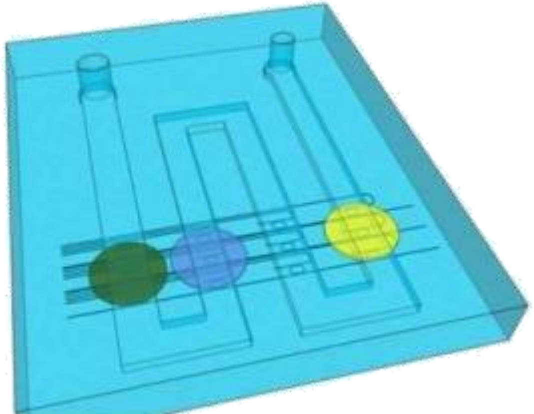


K. De Vos, LEOS AM 2009

RING RESONATOR BIOSENSORS: MULTIPLEXING

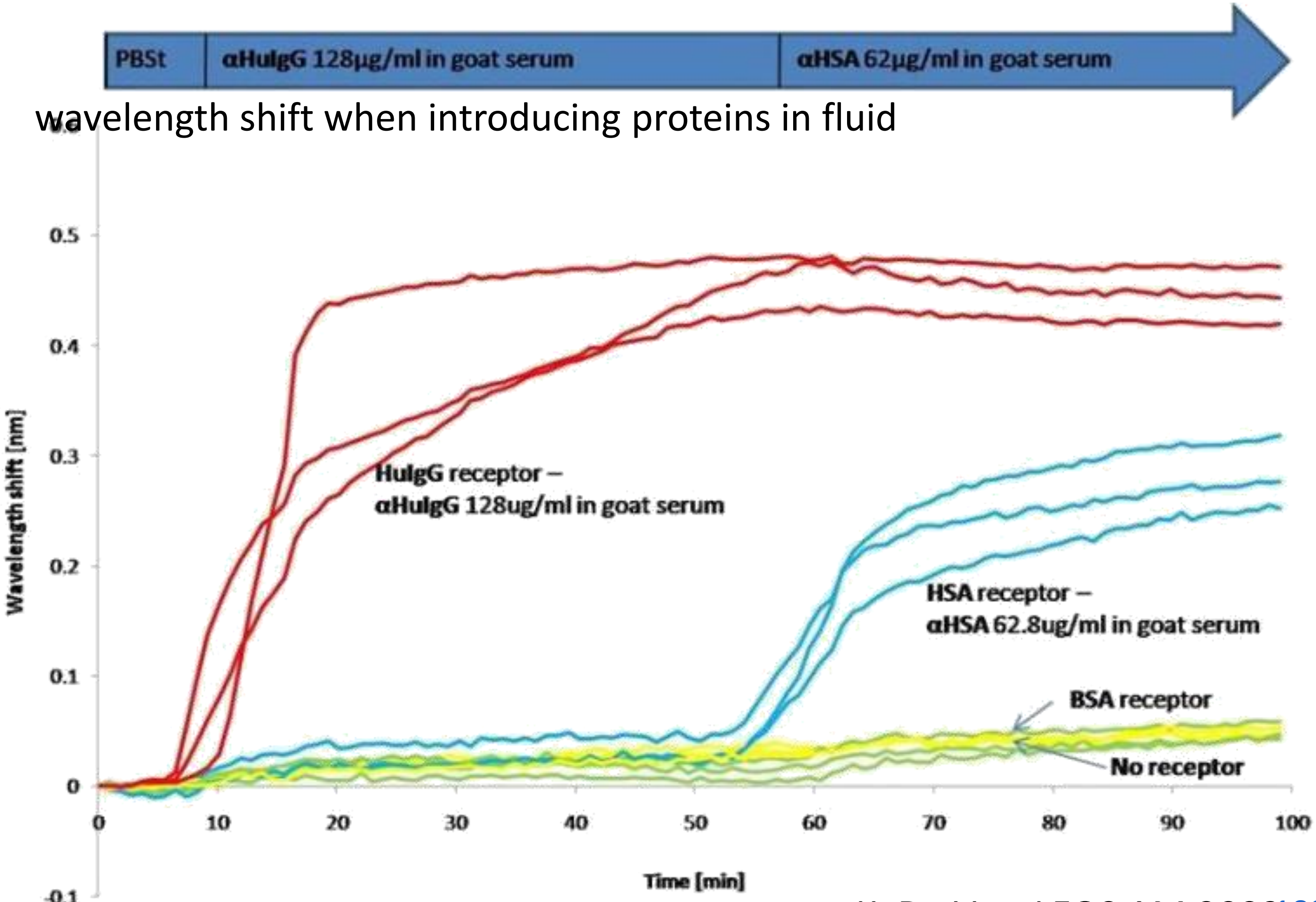






Different ring resonators functionalized for different protein reception in a single microfluidic channel

wavelength shift when introducing proteins in fluid



K. De Vos, LEOS AM 2009

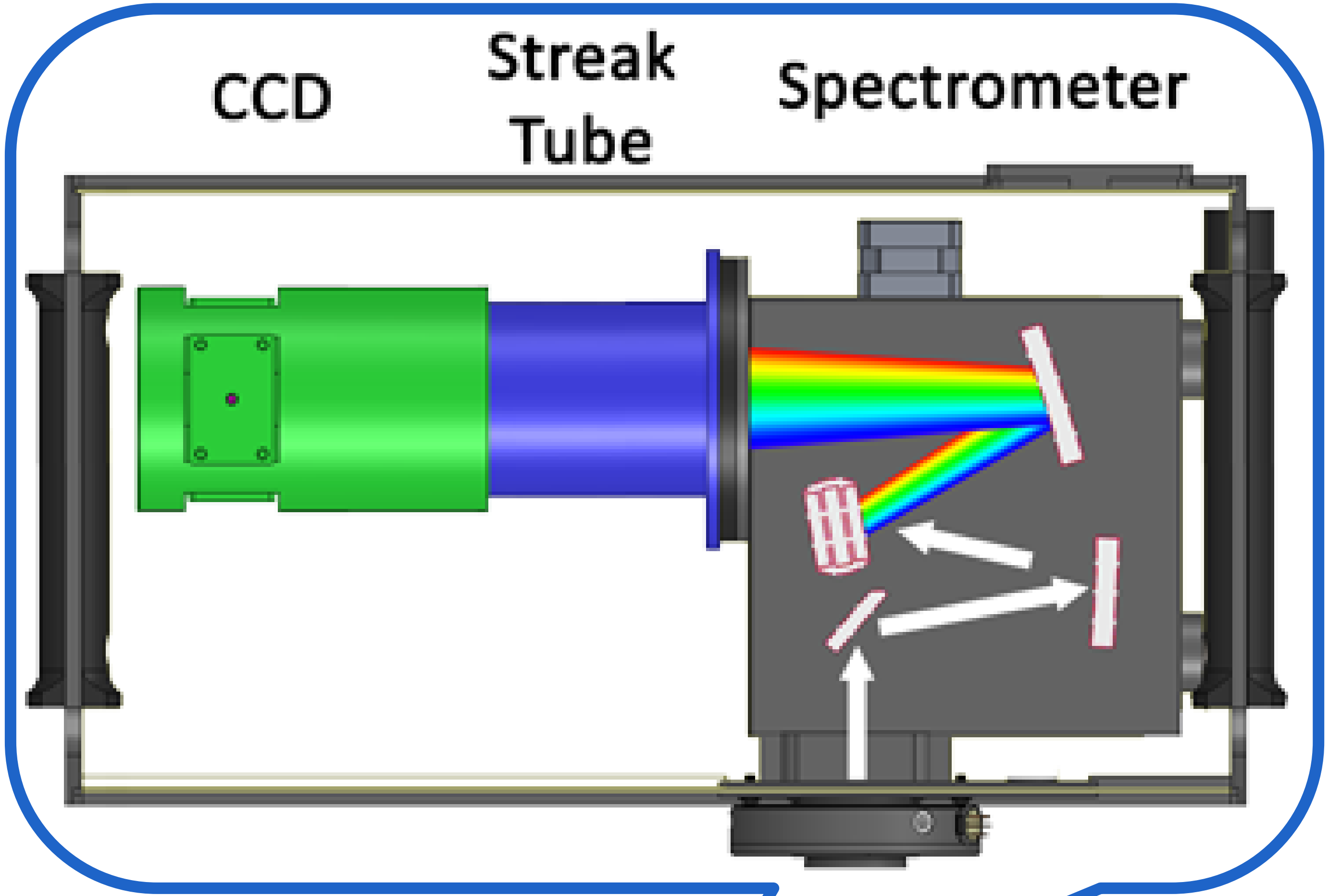
SPECTROMETRY - SPECTROSCOPY

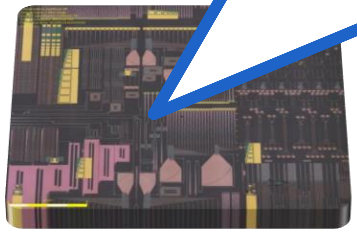
White light as input

Dispersive element (grating)

Many detectors (imager)

Resolution ~ size



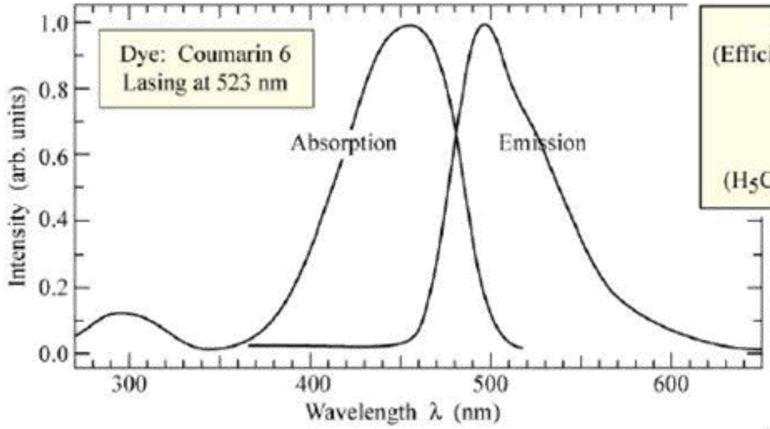


Photonic Chip

GHENT UNIVERSITY imec

DIFFERENT ABSORPTION SPECTRA

Dyes



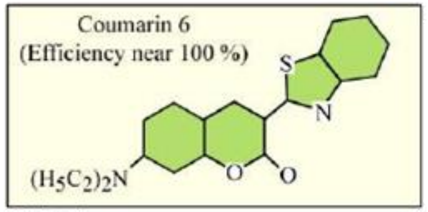


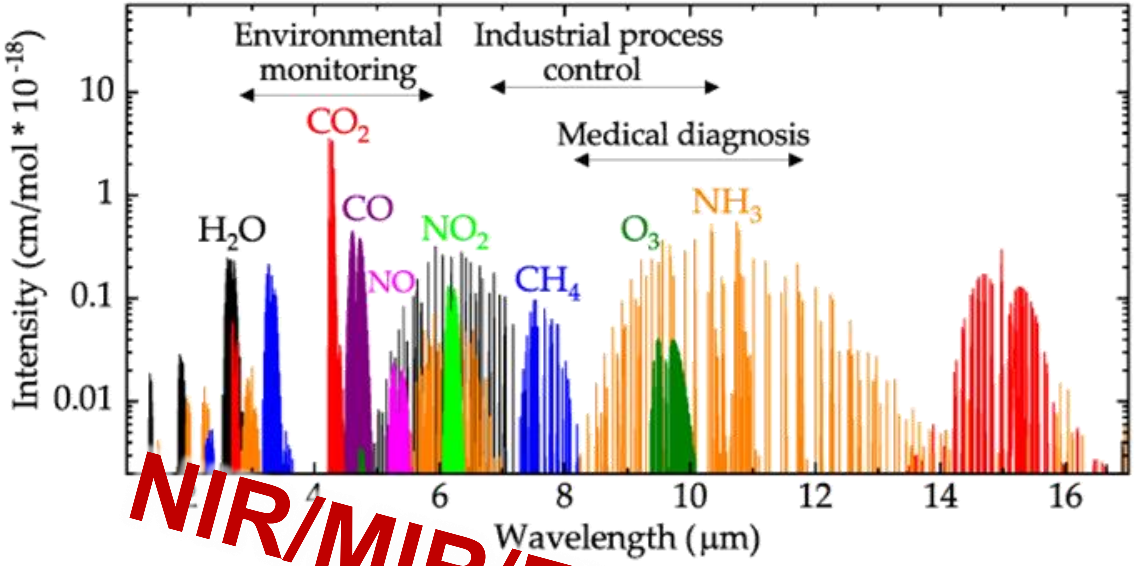
Fig. 21.3. Absorption and emission spectrum of the commercial dye "Coumarin 6". The inset shows the chemical structure of the dye molecule.

E. F. Schubert
Light Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

E. Schubert, Light Emitting Diodes (Cambridge UP)

UV/Visible/NIR

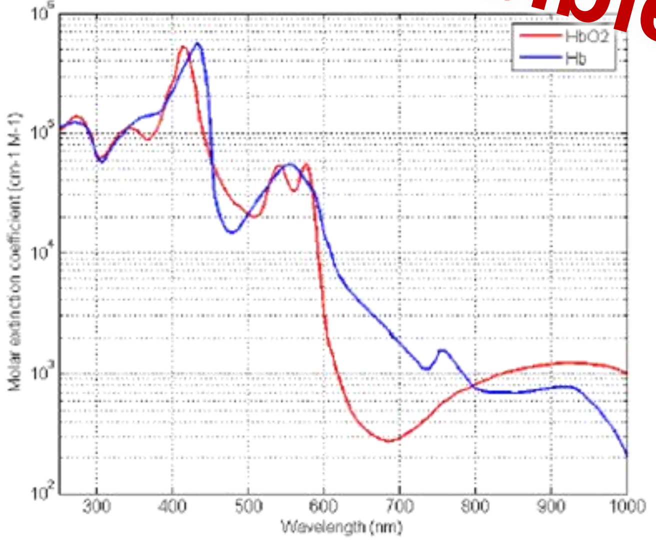
Gases



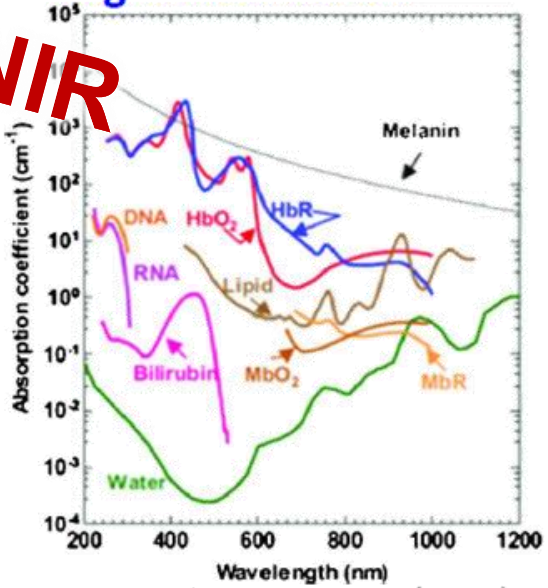
NIR/MIR/FIR

D. Popa, Sensors (2019) doi:10.3390/s19092076

Hemoglobin

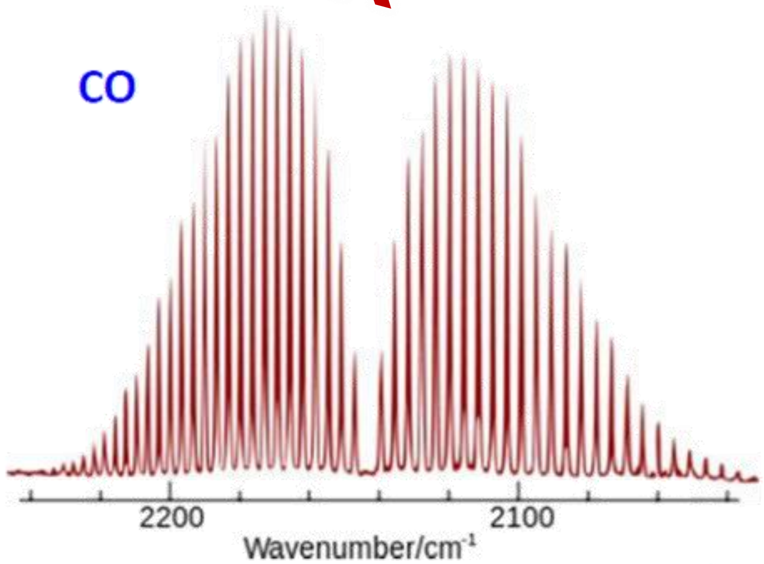


Biological molecules

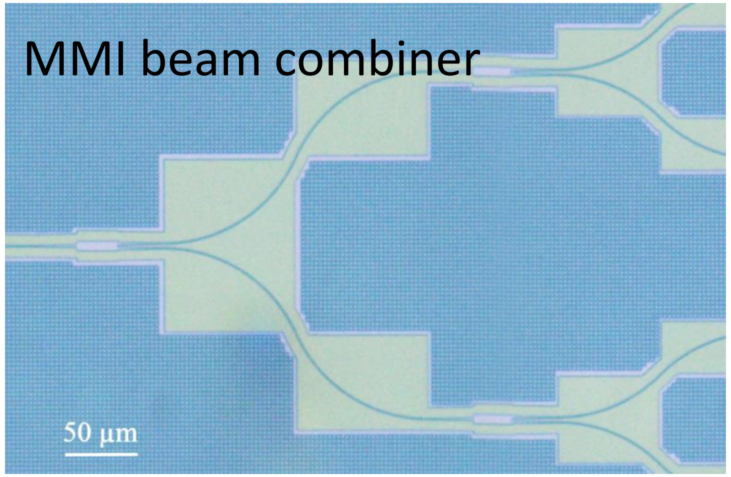


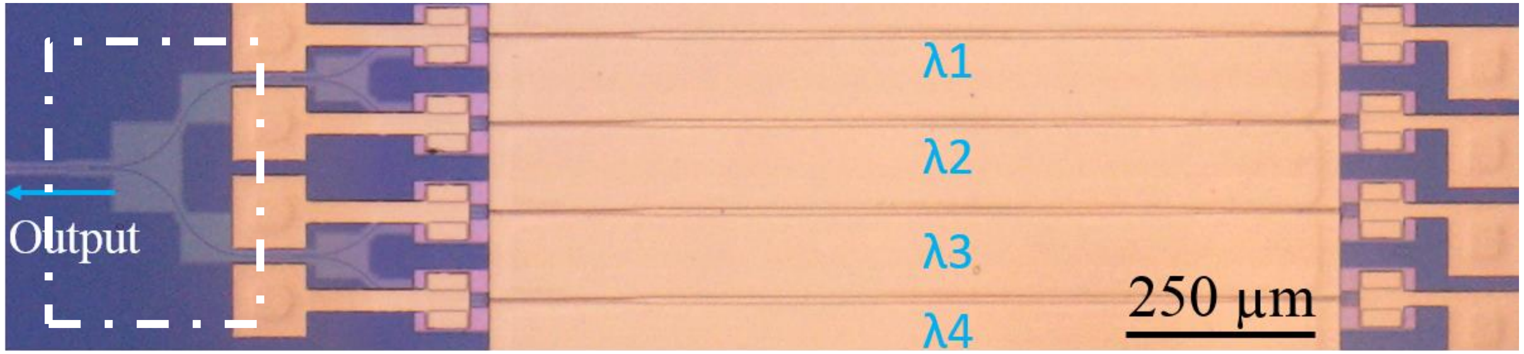
W. Liu, Photoacoustics (2016)

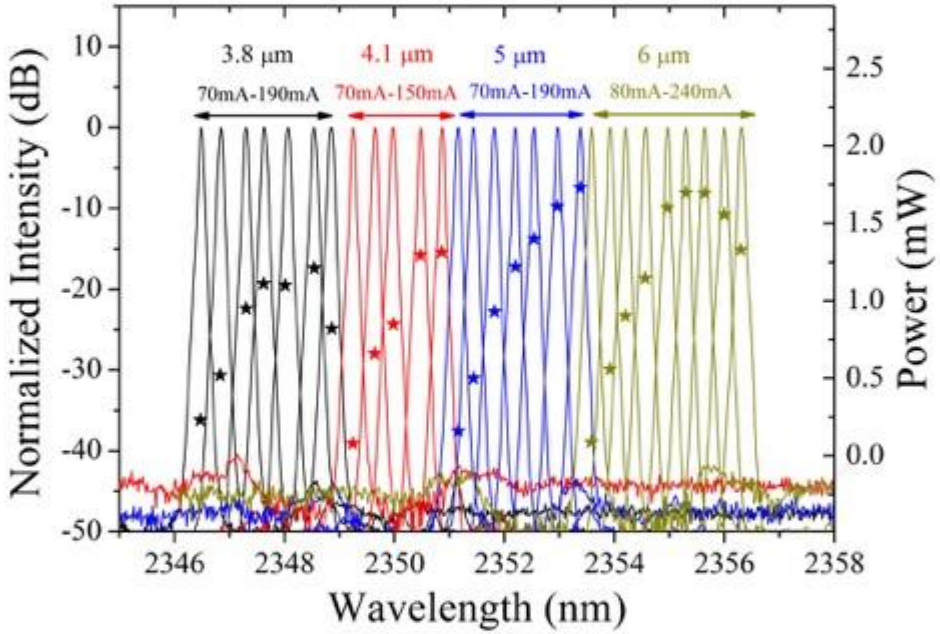
CO



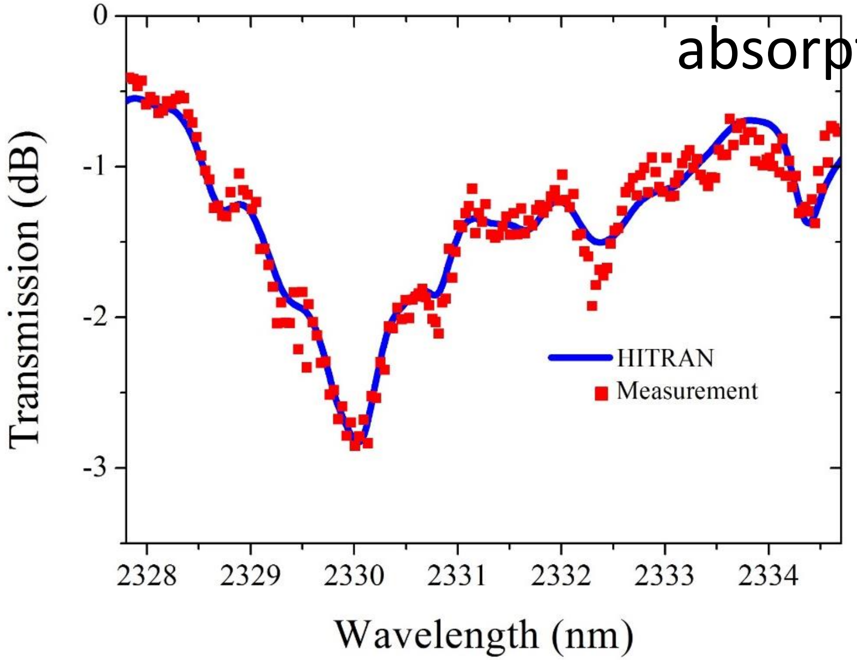
2.3 UM DFB LASER ARRAY SPECTROMETER







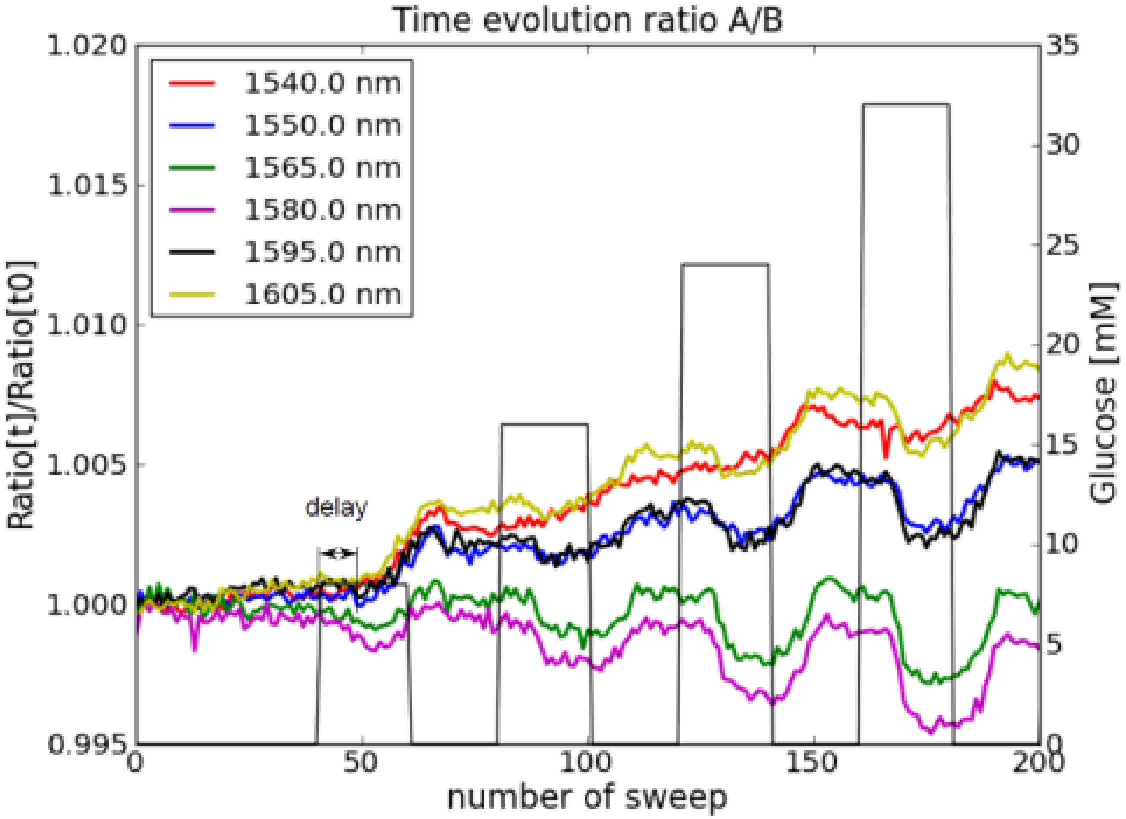
NH3 absorption



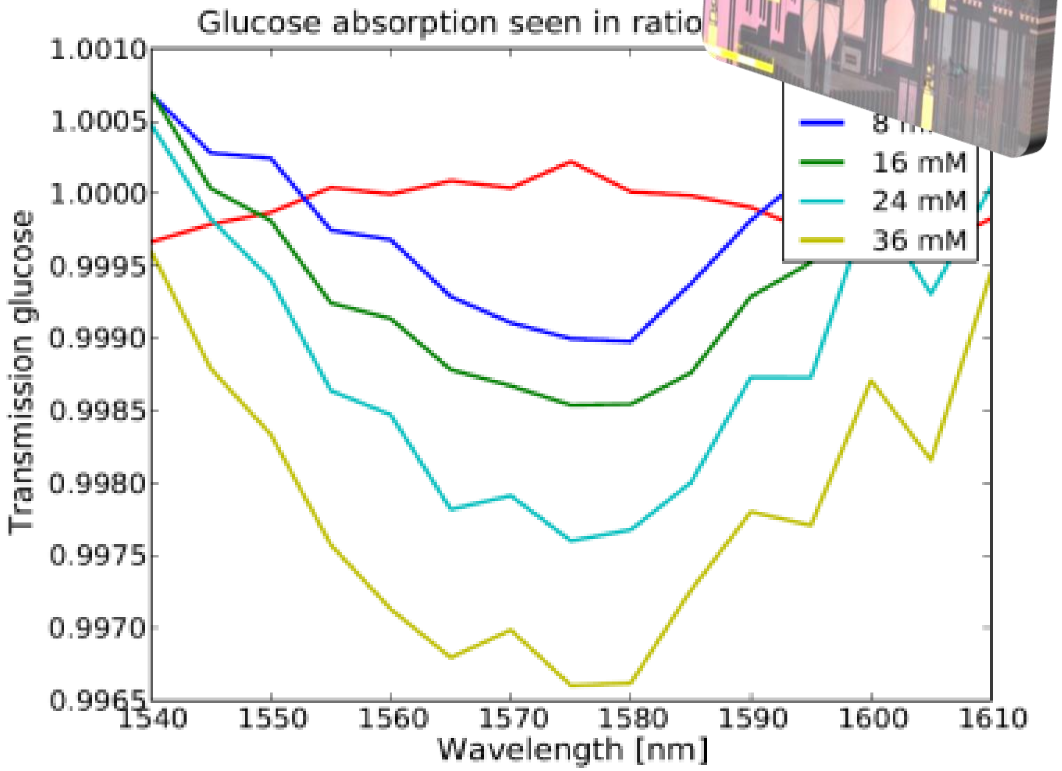
GLUCOSE ABSORPTION SPECTROSCOPY

Example: On-chip glucose monitoring

(using 4 on-chip spectrometers for 4 wavelength ranges)



Wavelength dependent slow drift remains



Absorption dip increases with increasing glucose concentration

PHOTONIC "CLINIC ON THE WRIST"

Rockley PHOTONICS

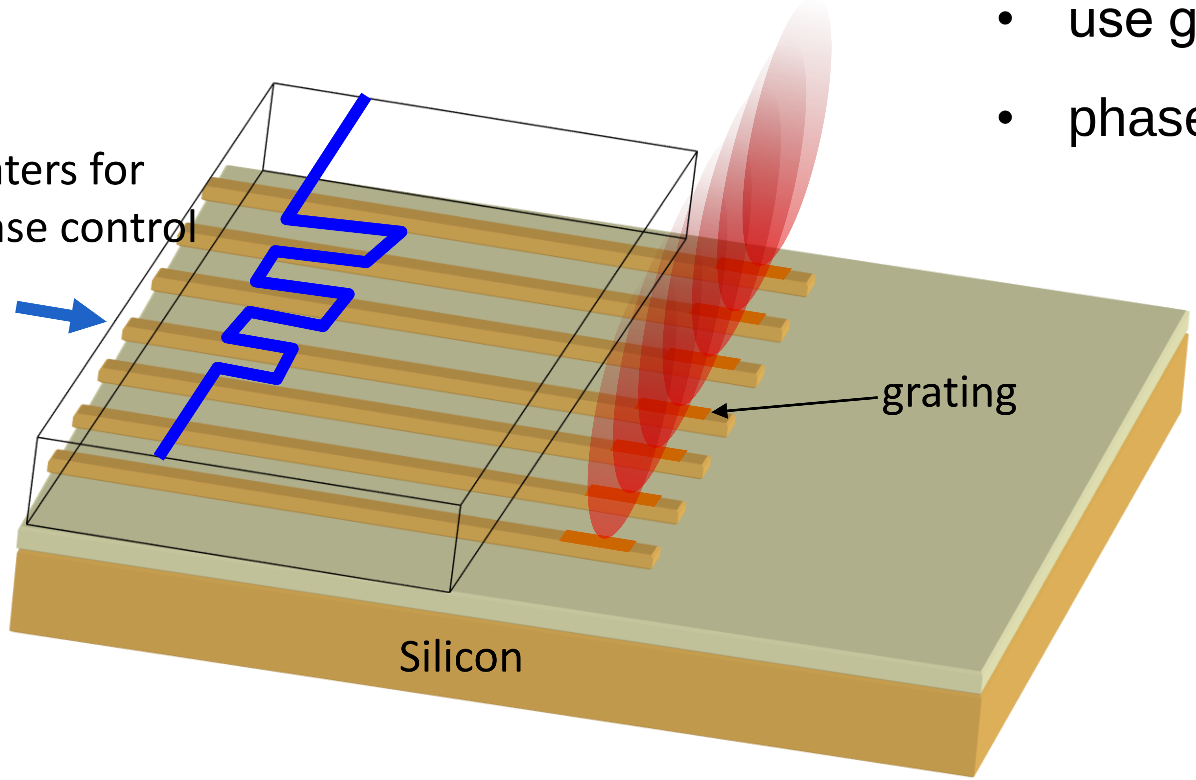
photonic chip to measure multiple quantities

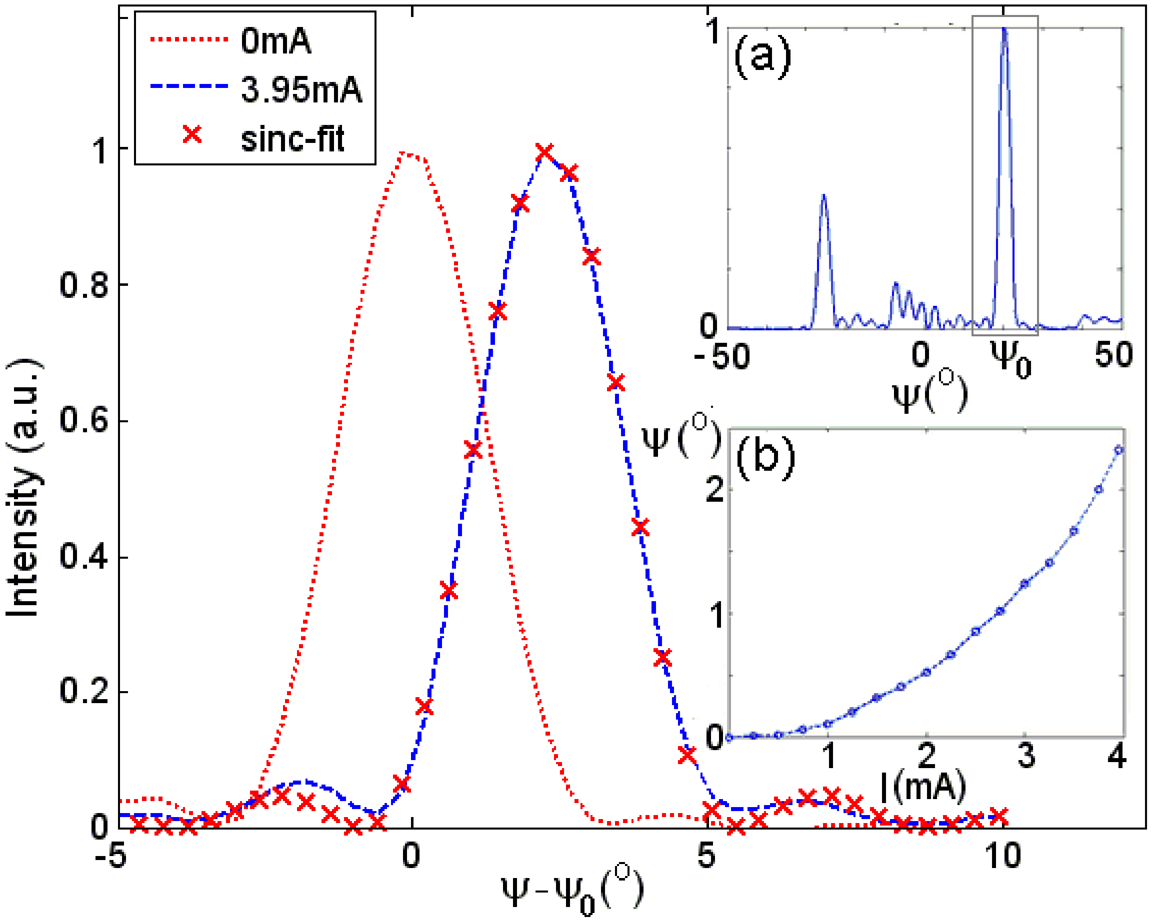
- O2-sat (oximetry)
- Glucose, lactate, alcohol
- Heartbeat, blood pressure

OFF-CHIP BEAM STEERING

Phased array beam steering:

- use grating couplers as 'antennas'
- phase delay controls steering angle



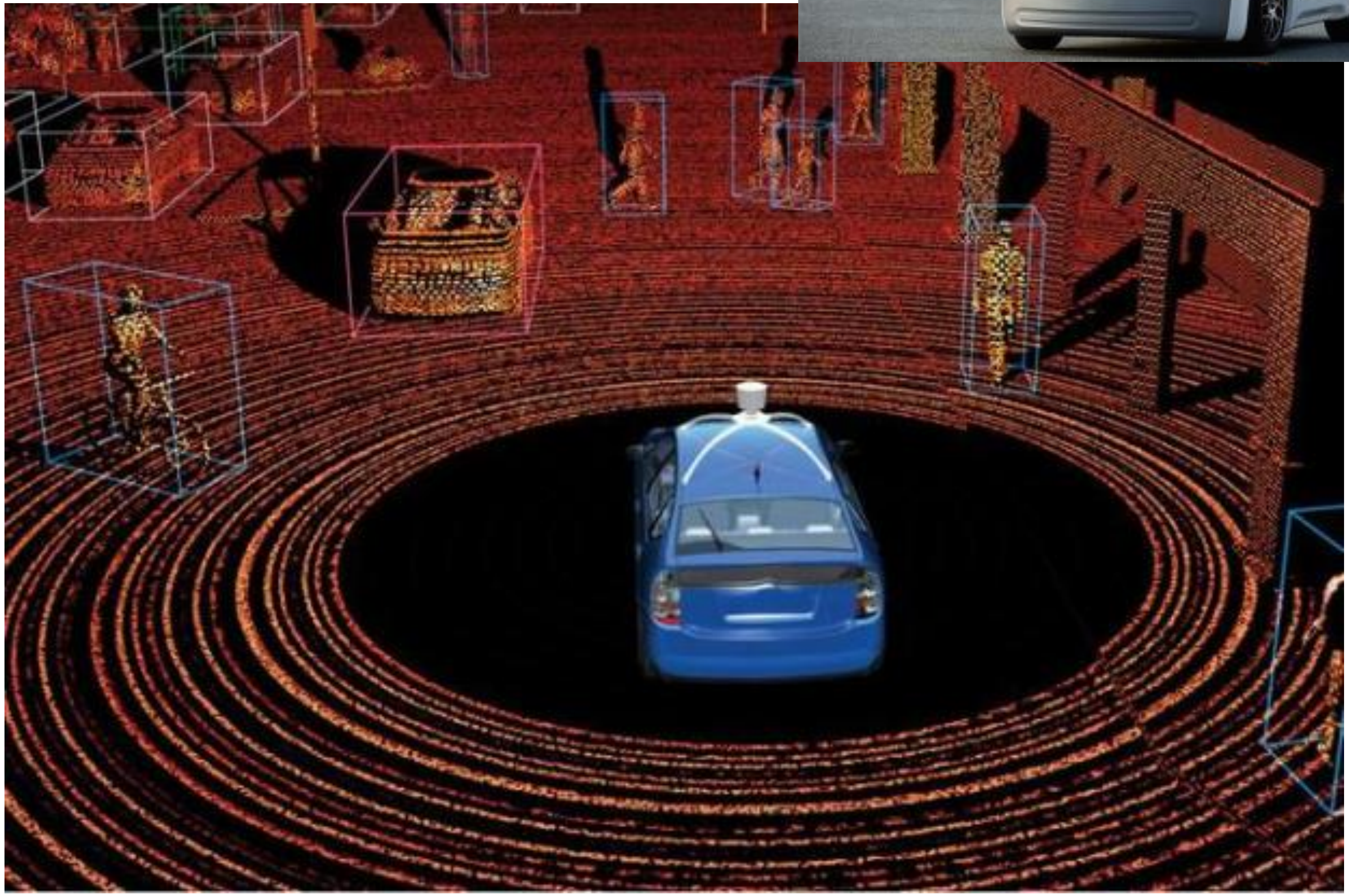


K. Van Acoleyen, Opt. Lett. 34, p.1477 (2009)

LIDAR

Radar with light.

Main application: autonomous vehicles



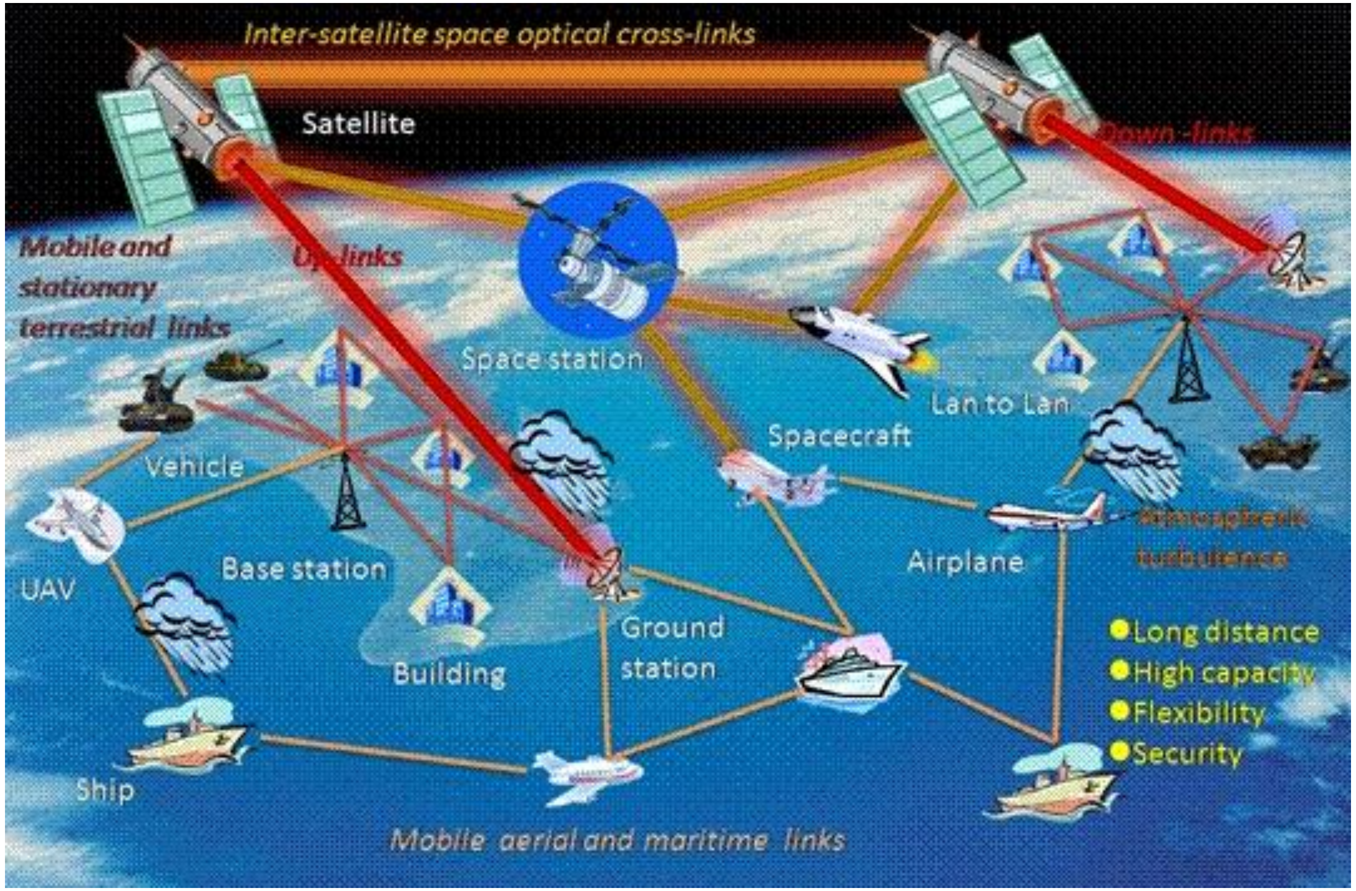
FREE-SPACE COMMUNICATION

Needs Pointing-Acquisition-Tracking

- beam forming
- beam steering

Optical phased arrays

- flat (pancake)
- lightweight
- no moving parts

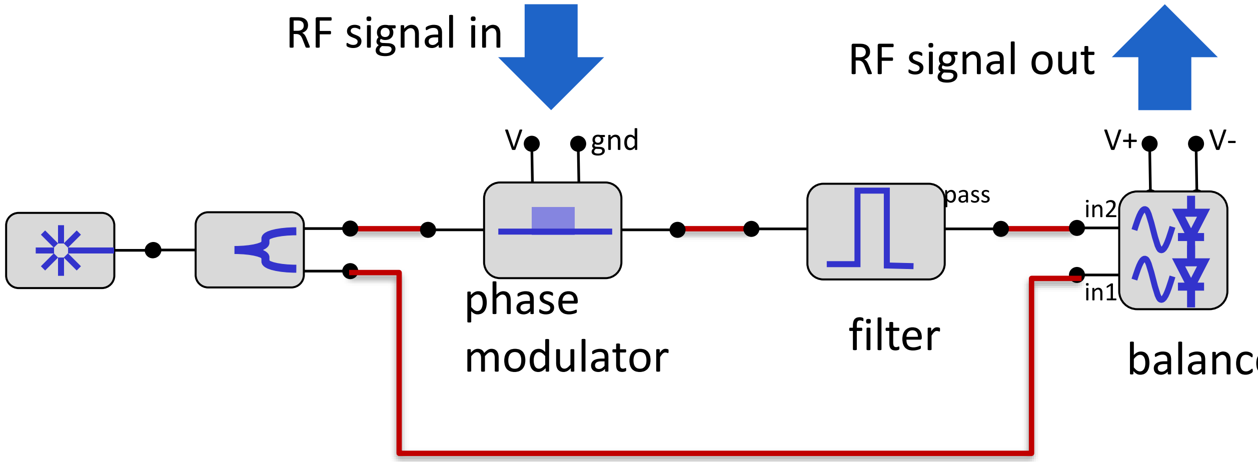


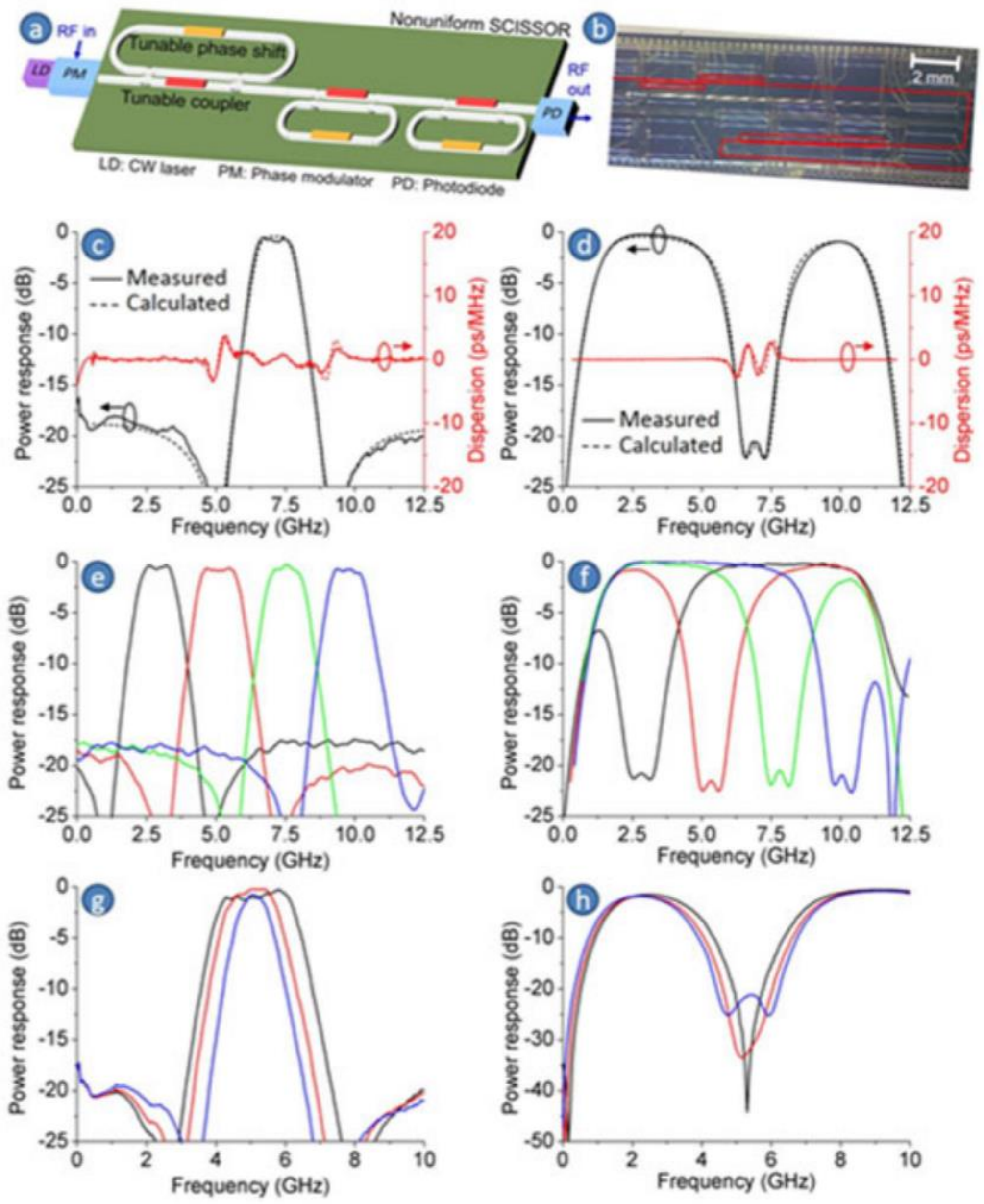
Photonic Microwave Processing

Process microwave signals in the optical domain:

- filtering, equalizing
- frequency conversion

Example: Triplex technology





Roeloffzen, JSTQE 2018

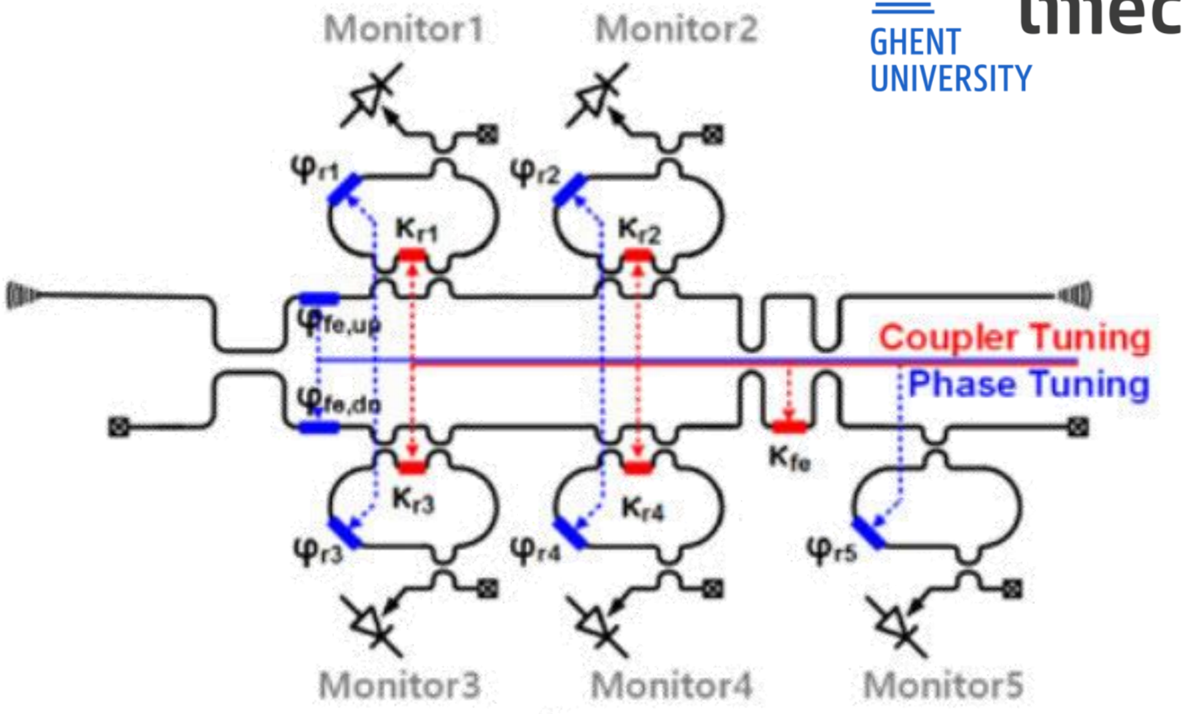
Programmable Microwave filter

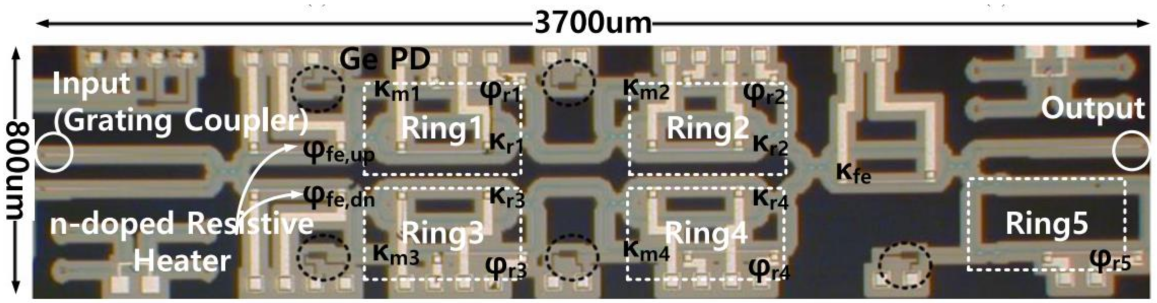
Programmable microwave filter

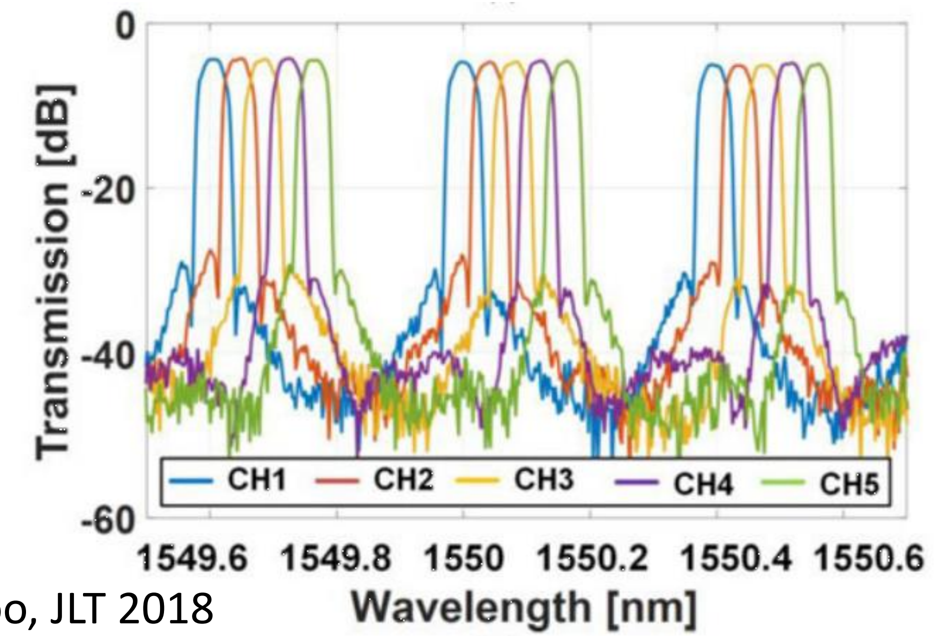
- select frequency band
- variable bandwidth
- variable frequency

Integrated tuners and monitors

Progressive configuration algorithms





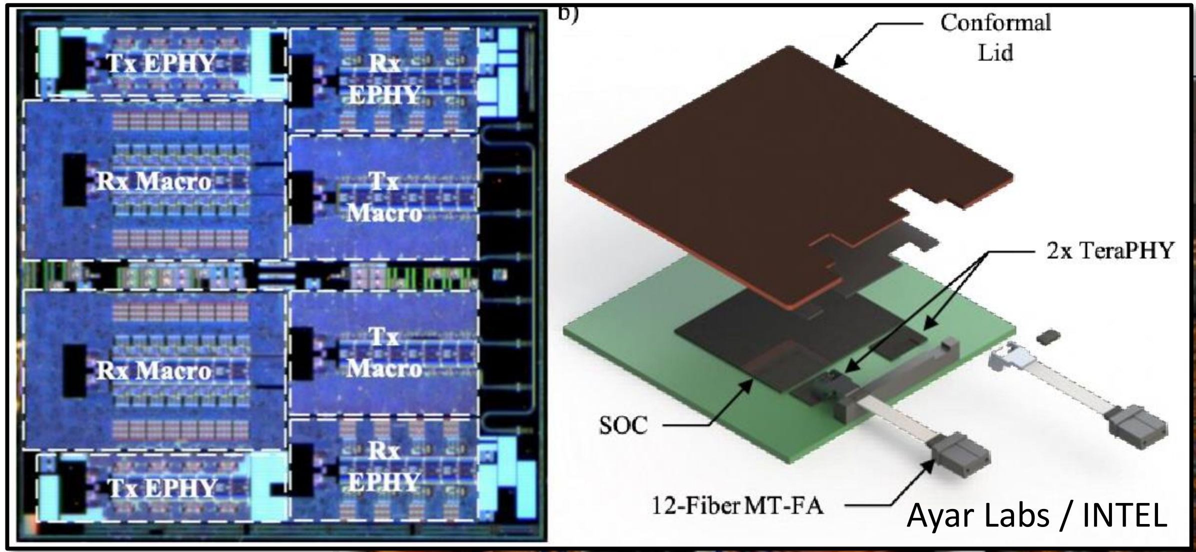


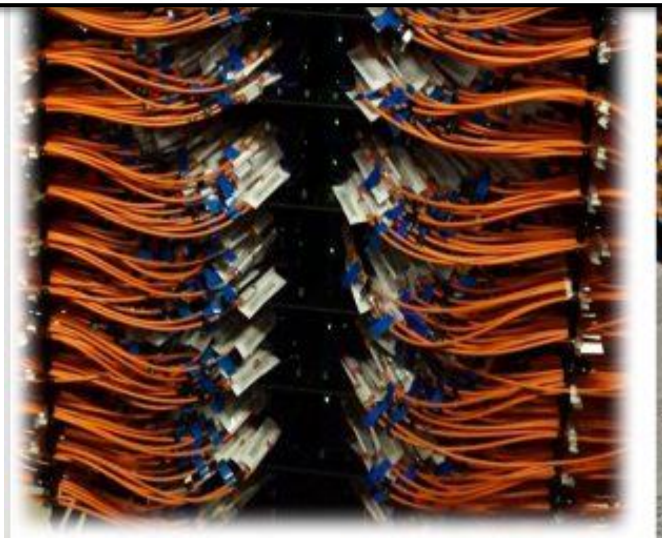
Choo, JLT 2018

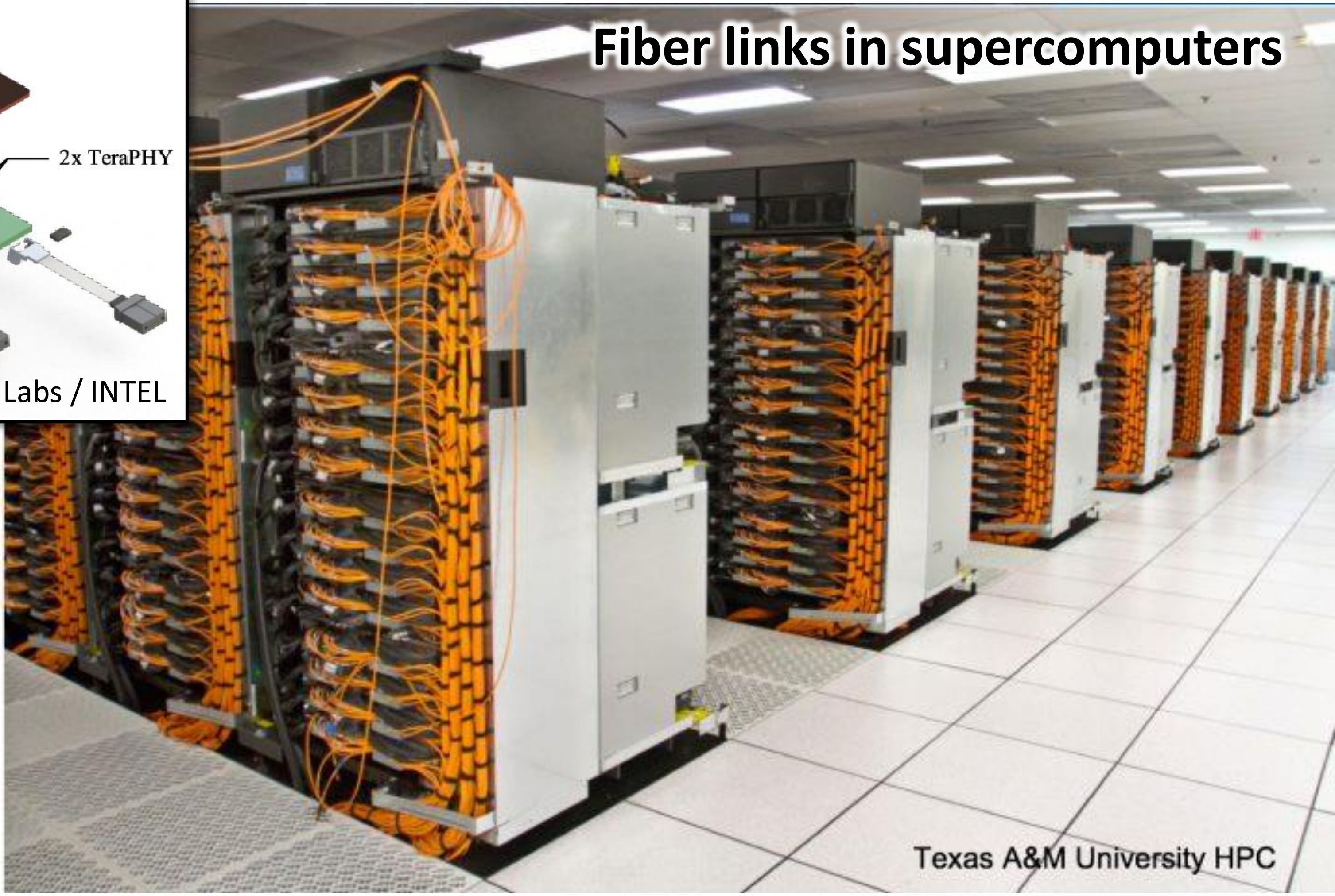
PHOTONICS IN COMPUTING?

mostly for communication

Package connections







COMPUTING WITH LIGHT?

Photons

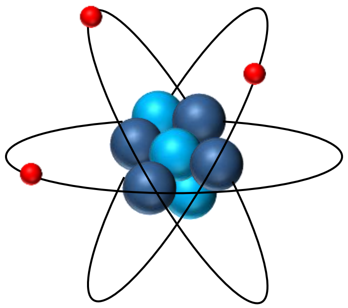
- Bosons
- Weak Interactions
- Poor nonlinearities

Linear analog operations

Electrons

- Fermions
- Strong interactions
- Strong nonlinearities

Binary logic



Can we do optical information processing?

source:Sony

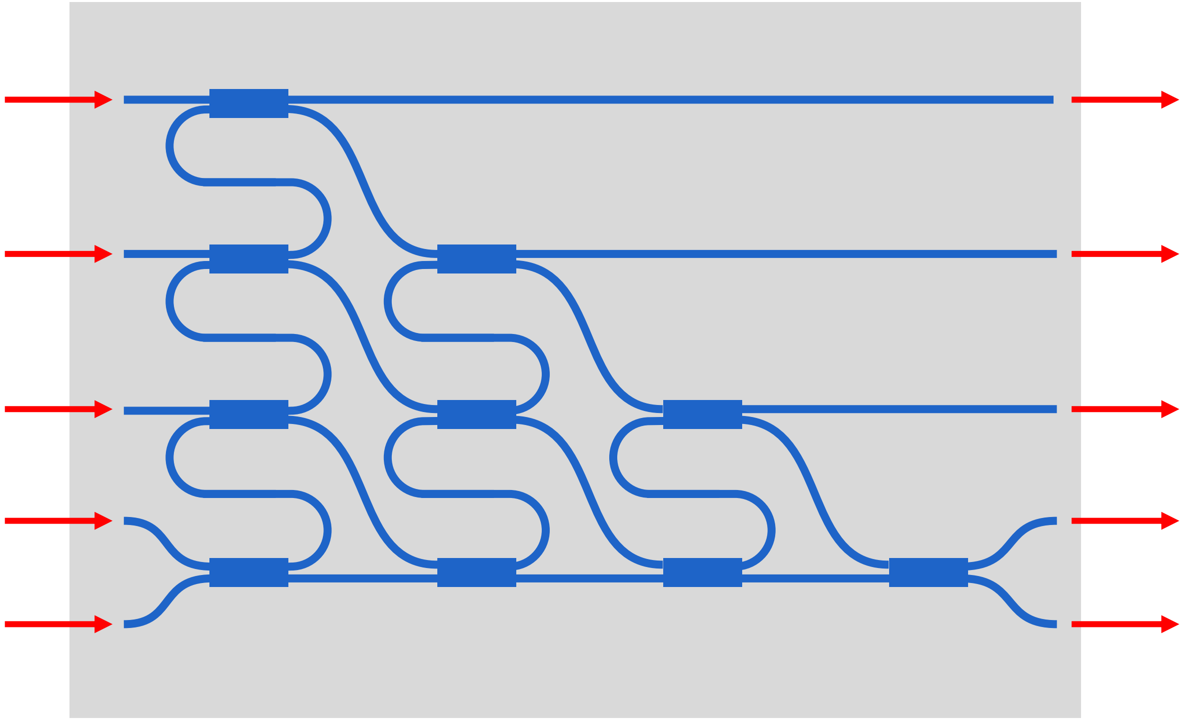
CALCULATIONS WITH PHOTONS?

multiport interferometers:

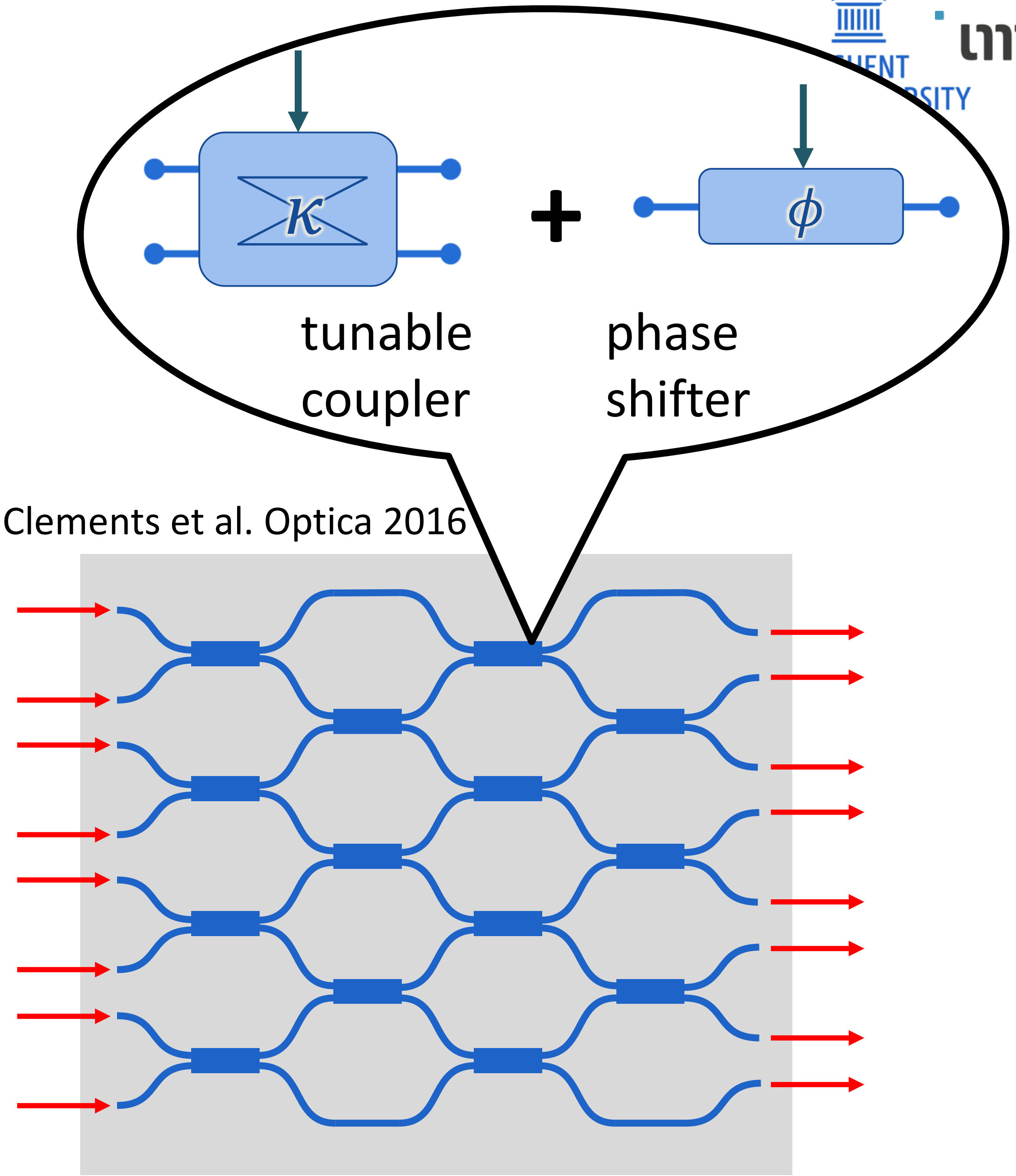
coupling many

inputs to many outputs

Miller. OpEx. 2013



Clements et al. Optica 2016

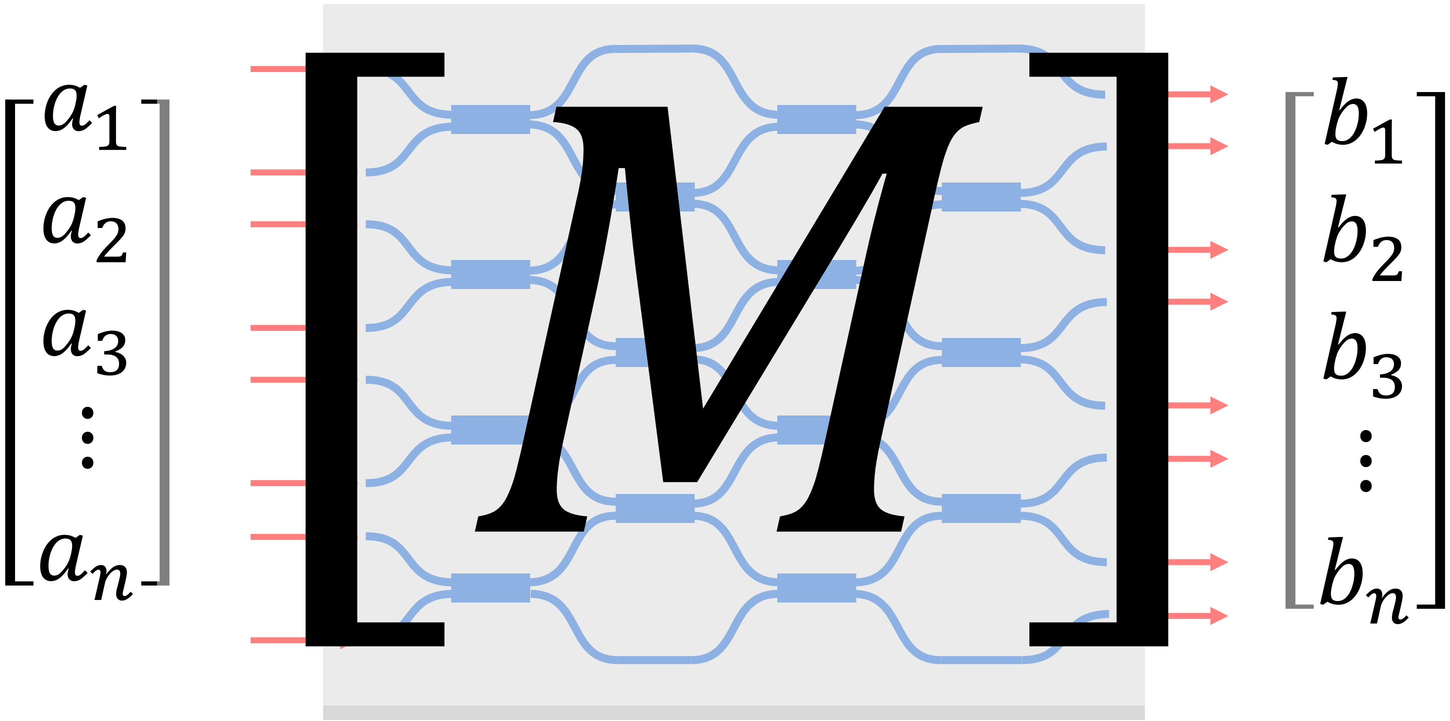


Calculations with Photons?

Multiport interferometers performs real-time matrix-vector product

(MAC operation)

$$\boldsymbol{b} = \boldsymbol{M} \cdot \boldsymbol{a}$$



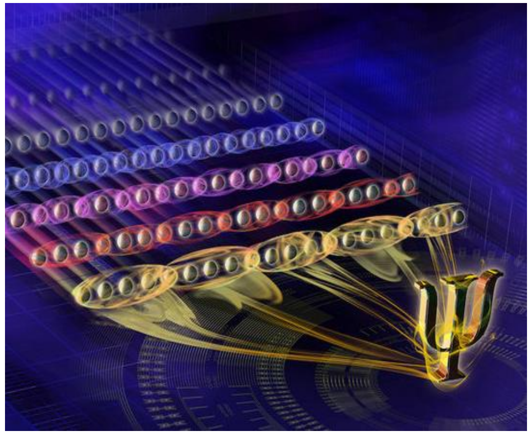
APPLICATIONS OF FORWARD-ONLY MESHES

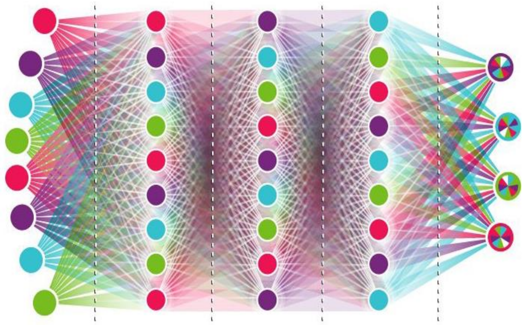
Linear circuit performs real-time matrix-vector product (MAC operation)

$$\boldsymbol{b} = \boldsymbol{M} \cdot \boldsymbol{a}$$

Basic operation in

- Pattern Recognition
- Linear Quantum Optics
- Artificial Neural Networks



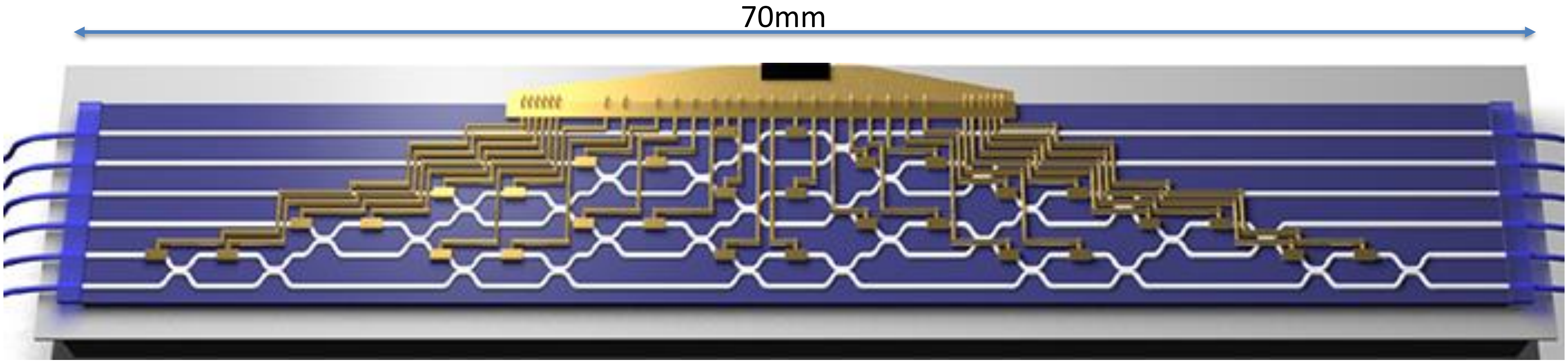


QUANTUM INFORMATION PROCESSING

Silica programmable linear circuit with thermo-optic tuners

6 x 6 universal linear circuit: can construct any T-matrix.

Consists of thermo-optic 2x2 MZI switches



source: U. Bristol

QUANTUM OPTIC PROCESSING: SINGLE PHOTONS

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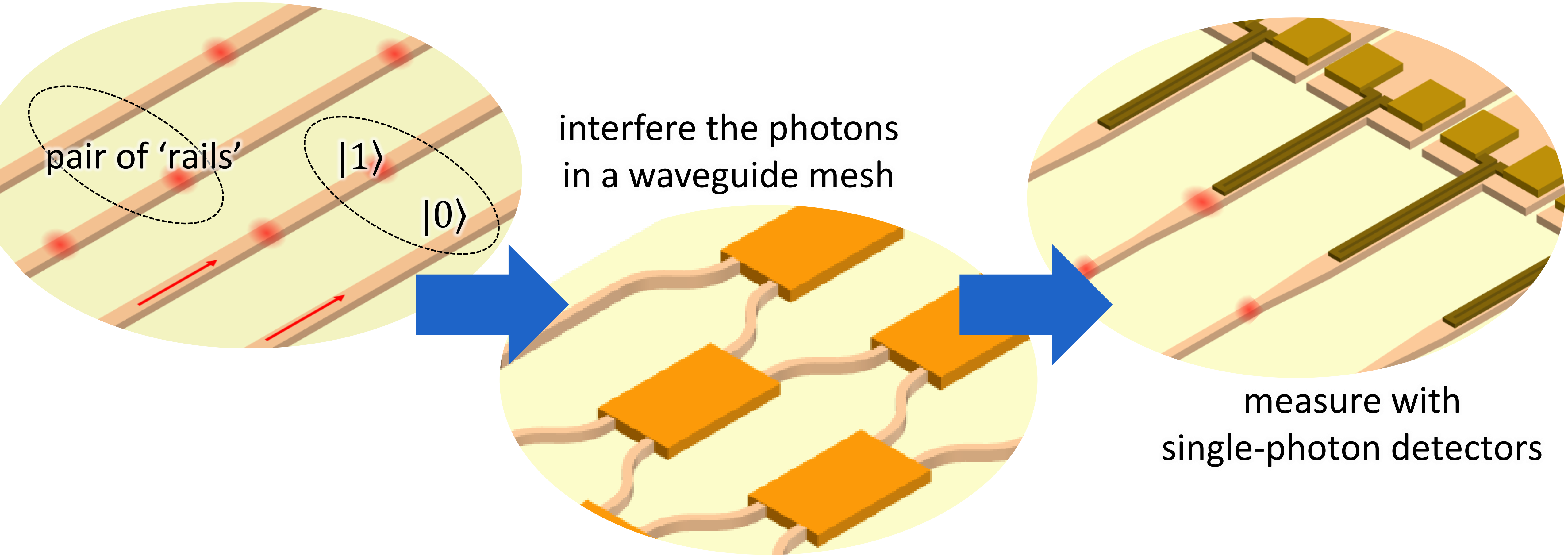
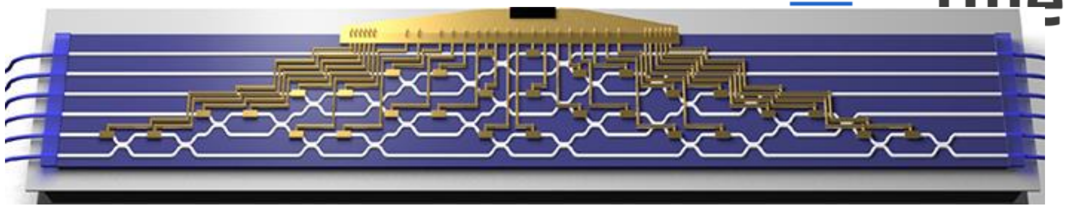
Encoding qubits: single photons

- e.g. polarization or position (in one of two waveguide 'rails')



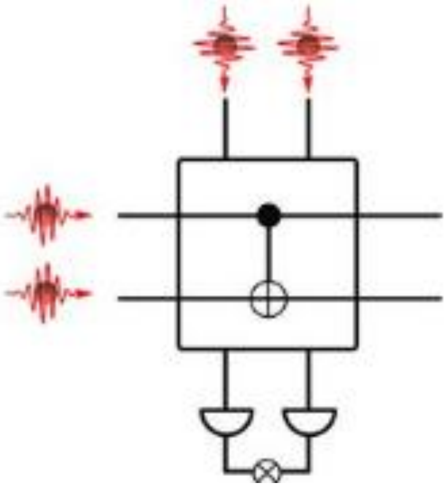
QUANTUM INFORMATION PROCESSING

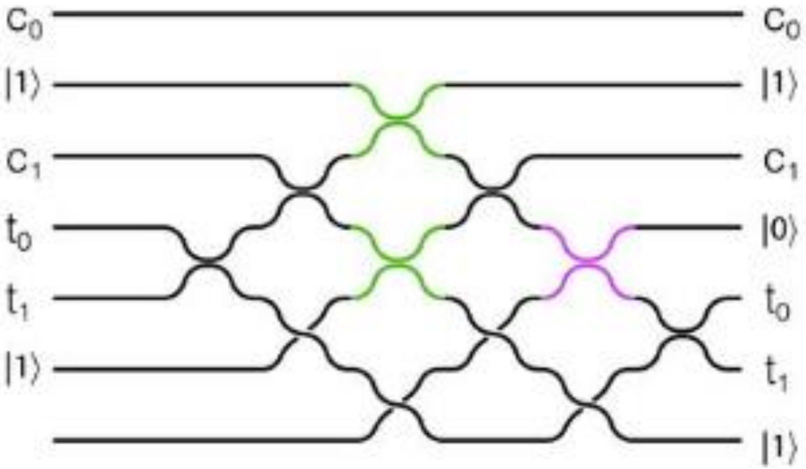


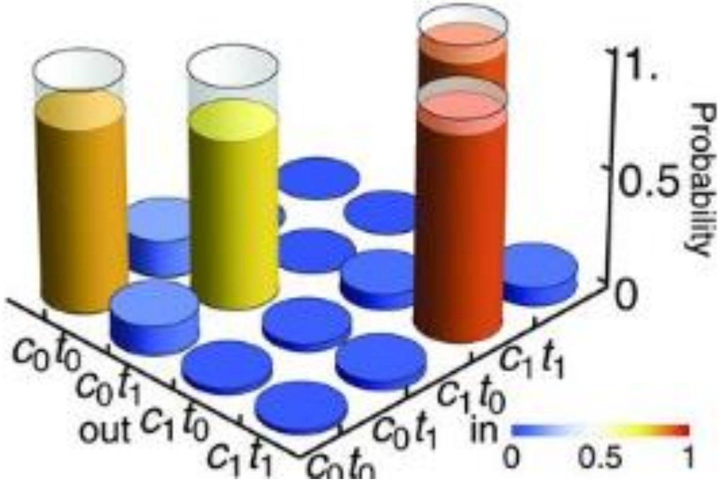
Heralded CNOT gate

- heralded: using photon pairs to detect whether a photon is present
- Qubit encoding on rails: photon is either in one waveguide or the next (or both)
- Controlled NOT gate

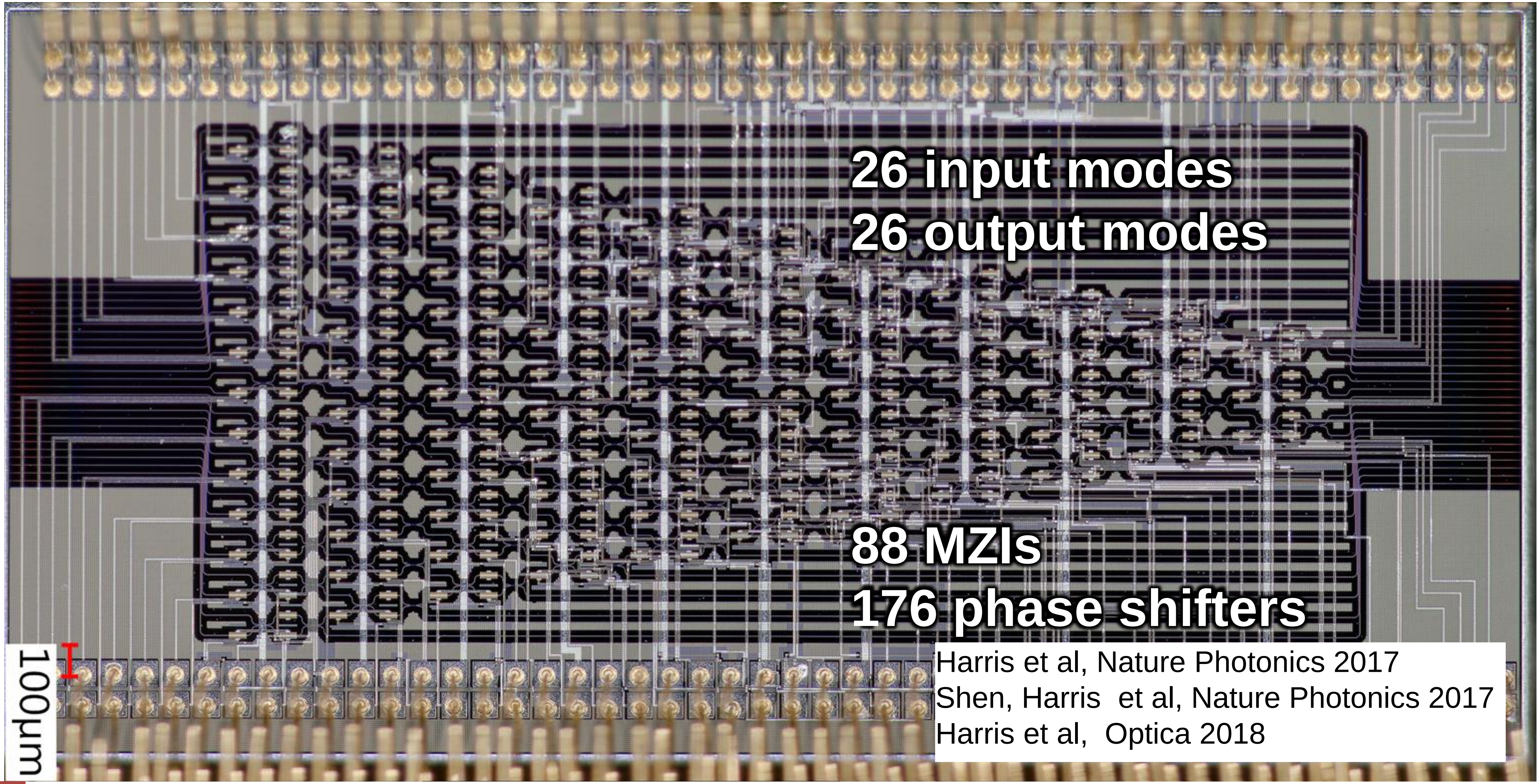
input x	input y	output x	output y+x
$\|0\rangle$	$\|0\rangle$	$\|0\rangle$	$\|0\rangle$
$\|0\rangle$	$\|1\rangle$	$\|0\rangle$	$\|1\rangle$
$\|1\rangle$	$\|0\rangle$	$\|1\rangle$	$\|1\rangle$
$\|1\rangle$	$\|1\rangle$	$\|1\rangle$	$\|0\rangle$







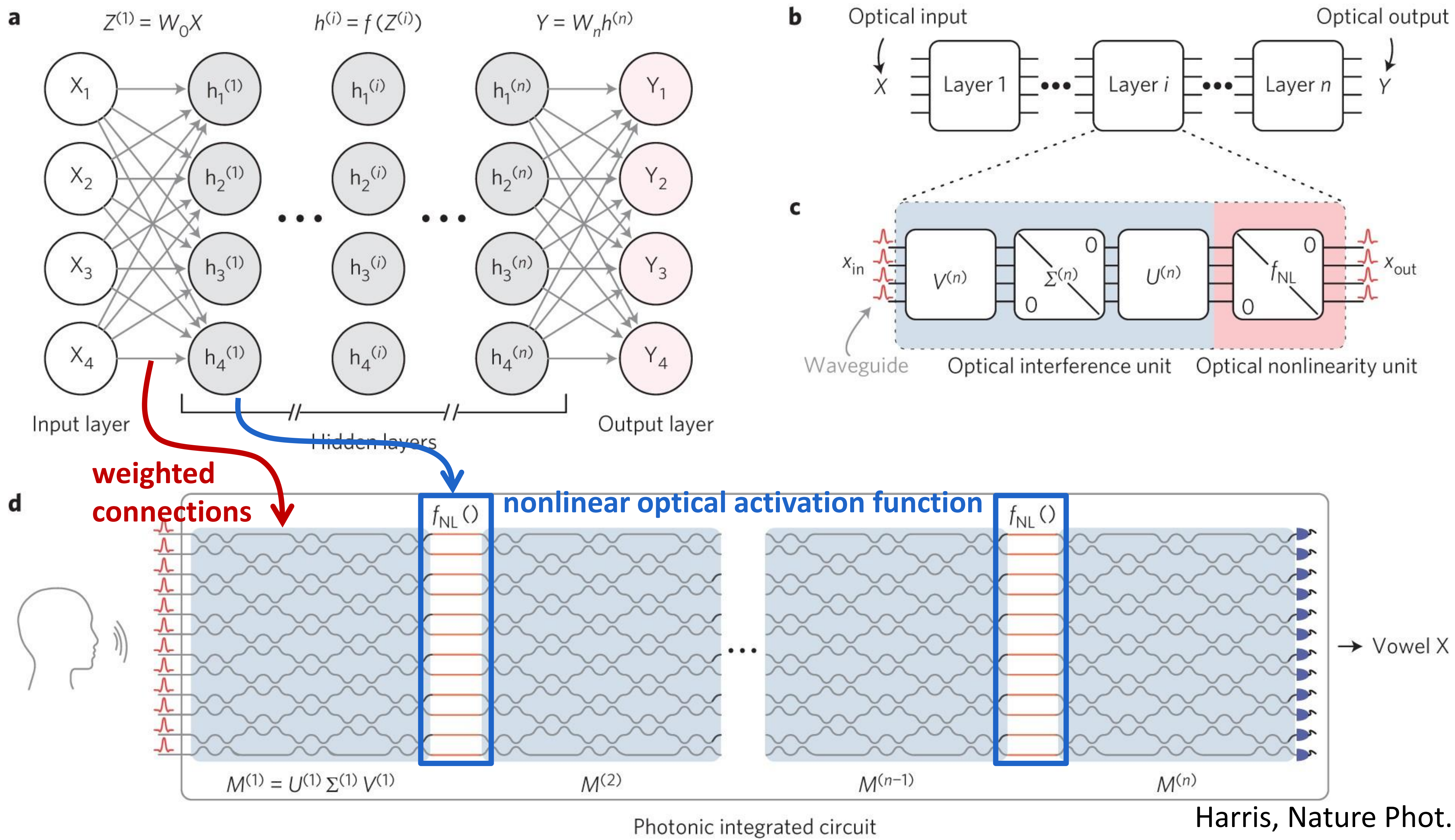
LARGE-SCALE FORWARD-ONLY MATRIX CIRCUIT



Harris et al, Nature Photonics 2017
Shen, Harris et al, Nature Photonics 2017
Harris et al, Optica 2018

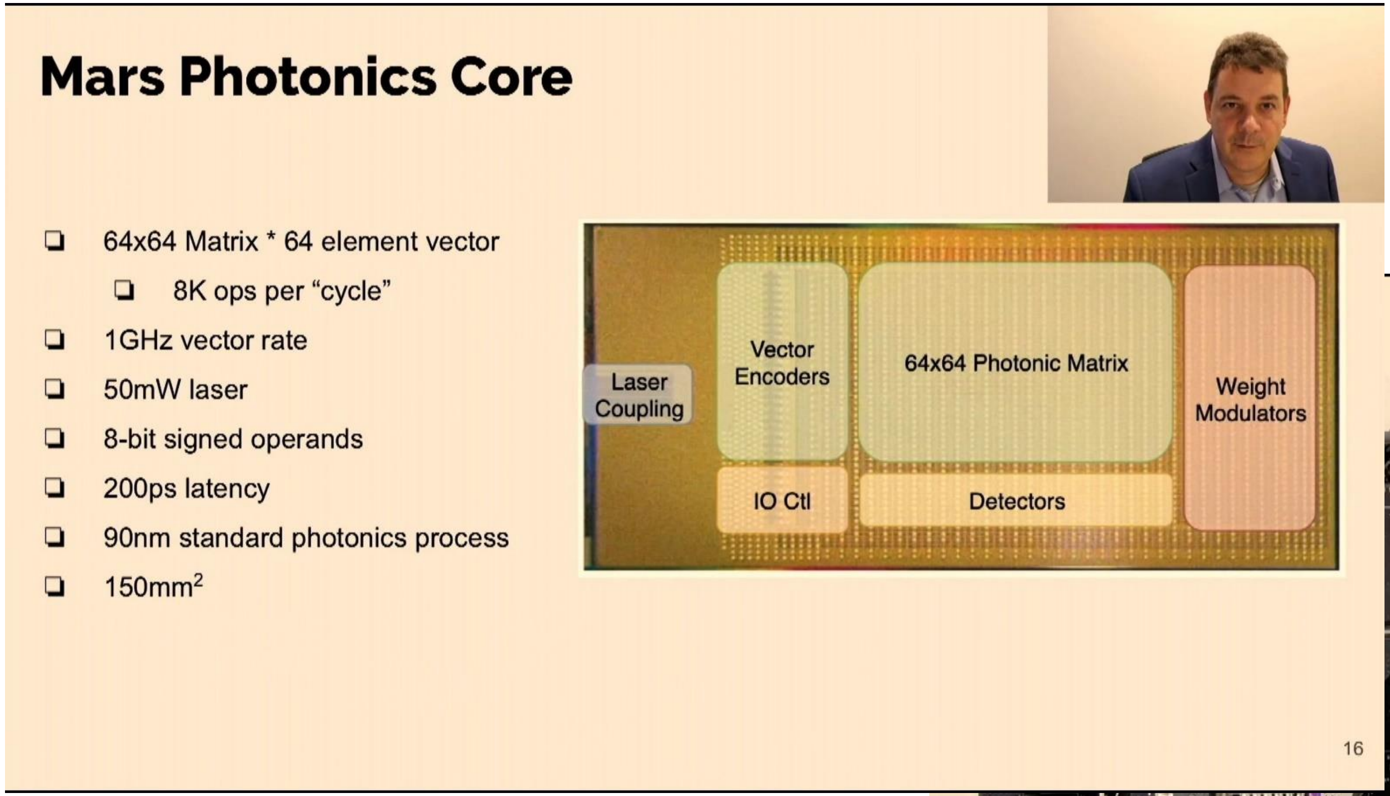
Michael Hochberg (opsis), Michael Fanto (RIT), Paul Alsing (AFRL), Stefan Preble (RIT), Philip Walther (U. Vienna)

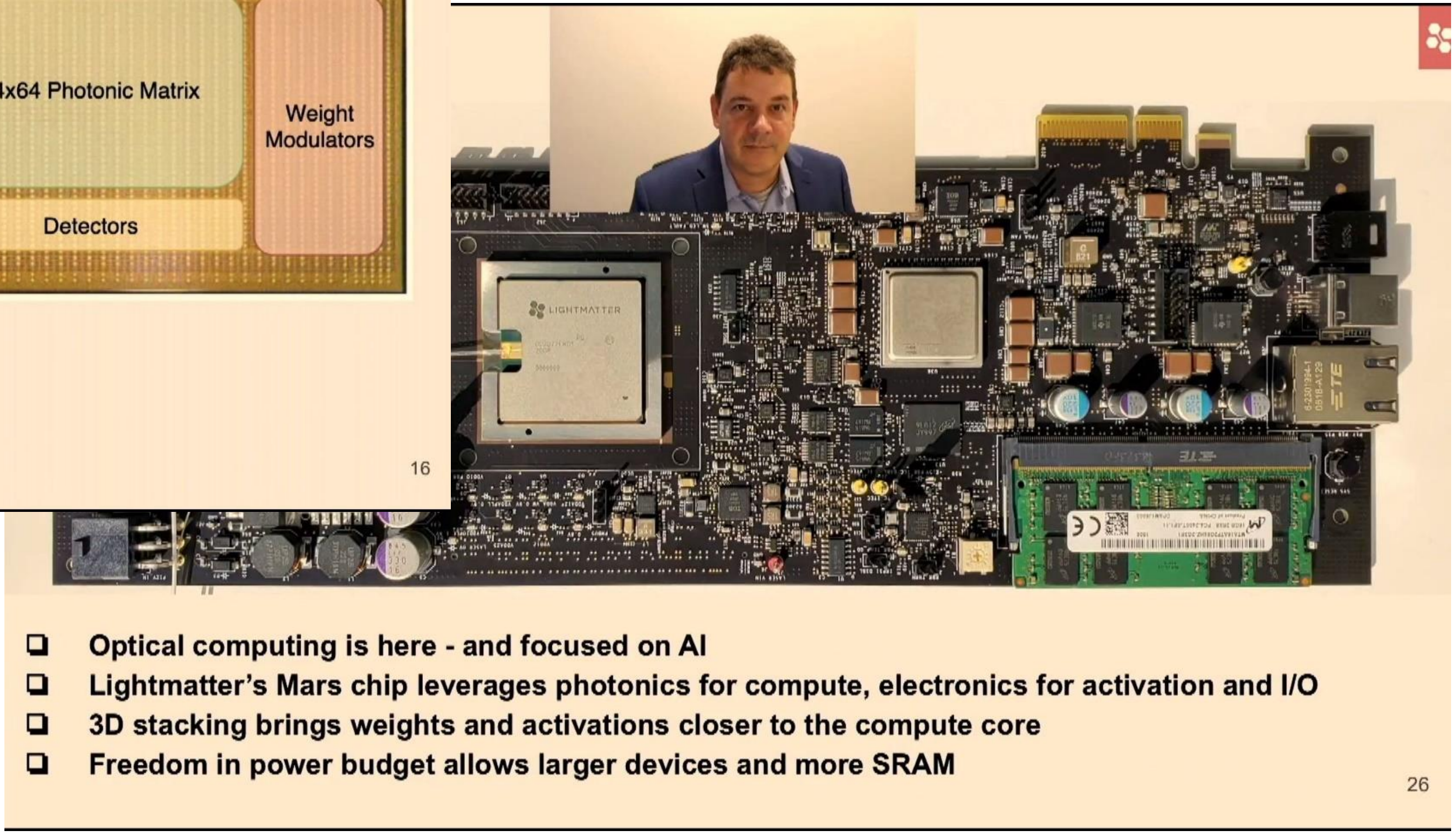
NEURAL NETWORK ACCELERATORS



Harris, Nature Phot. 2018

LIGHTMATTER: PHOTONIC CIRCUITS FOR AI ACCELERATORS

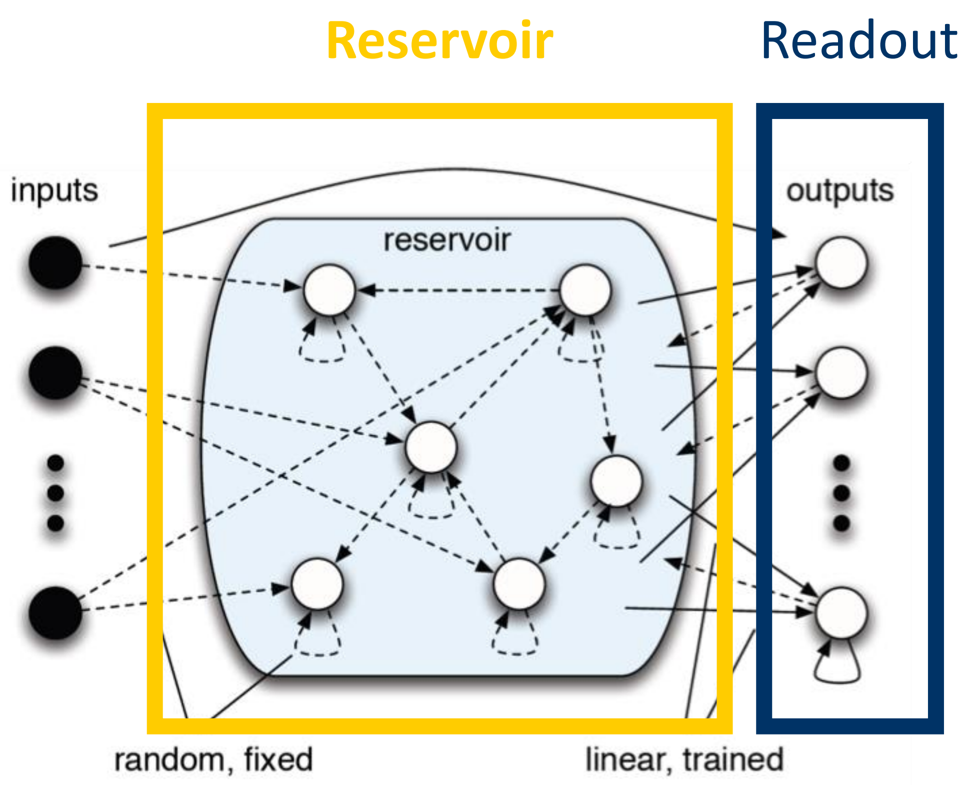


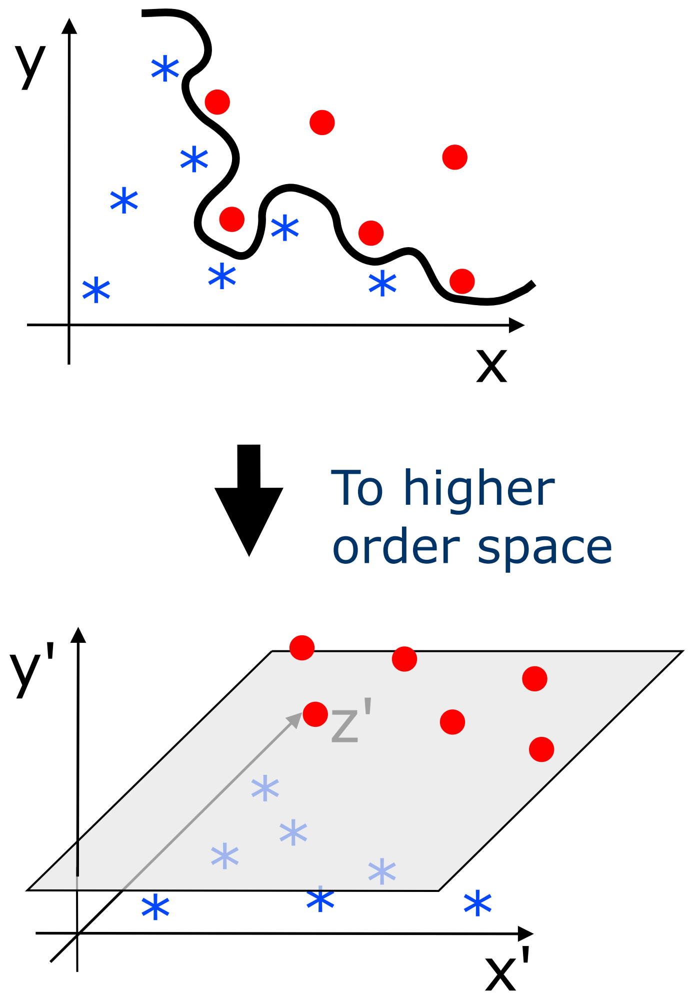


https://www.anandtech.com/show/16010/hot-chips-2020-live-blog-silicon-photonics-for-ai-600pm-pt

RESERVOIR COMPUTING

Don't train the neural network, only train the linear readout

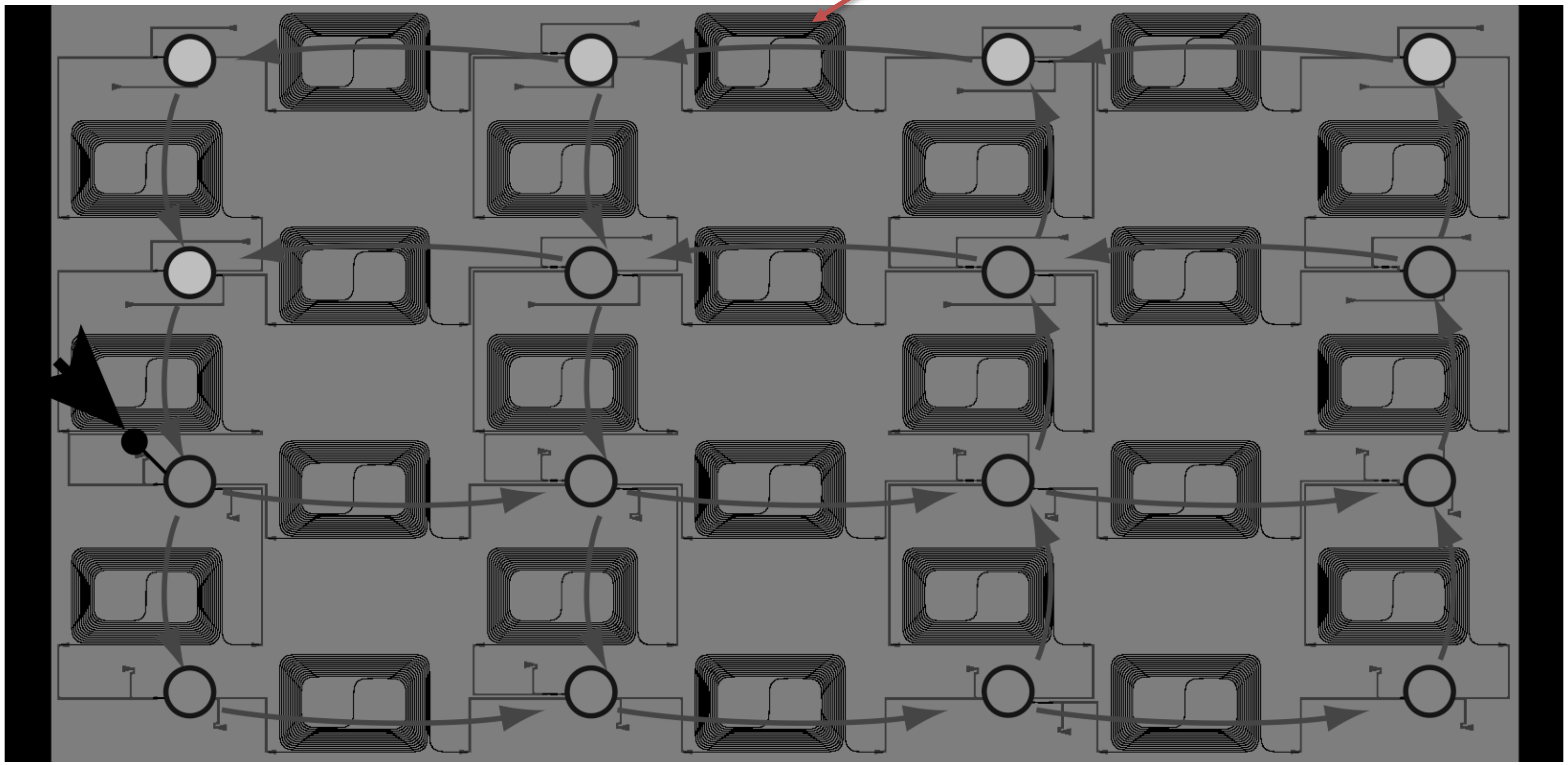




Silicon Photonics Reservoir

- Giant multipath interferometer
- No active power consumption inside chip

Long spiral waveguides to 'slow down' the response



Vandoorne et al. 2014

RESERVOIR COMPUTING TO EQUALIZE DISTORTED SIGNAL

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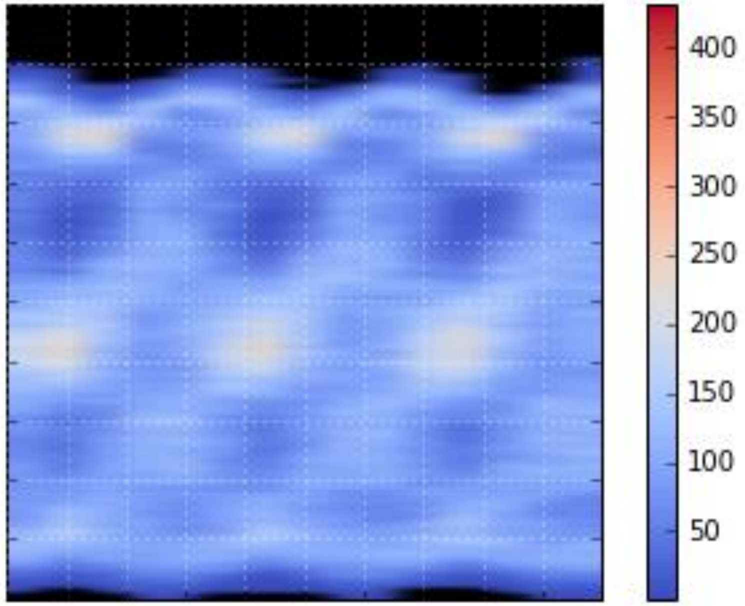
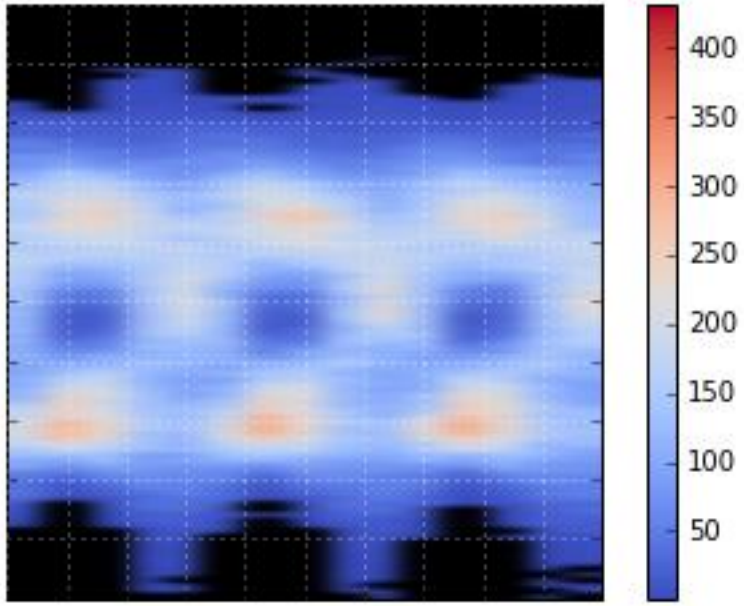
Traditional approach: digital signal processing (power hungry, speed limited)

Distorted signal



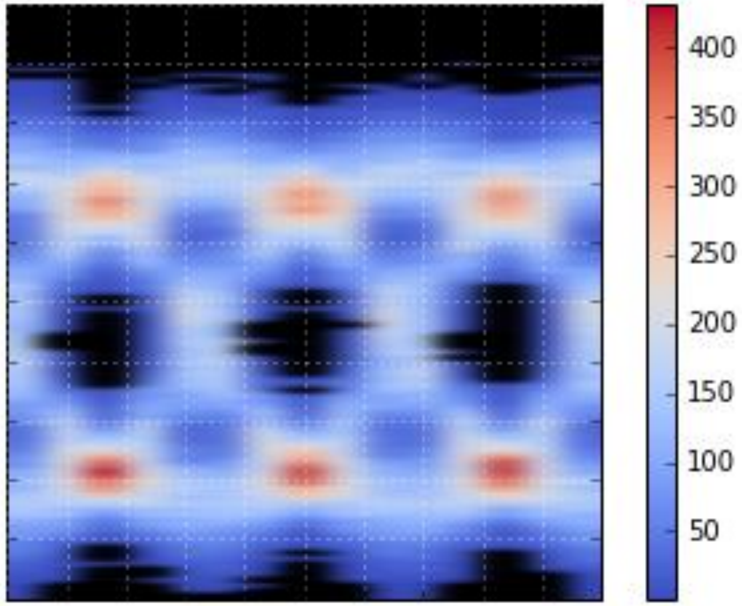
Linear equalizer

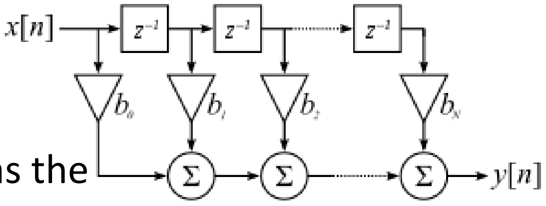
BER: 2.25 x 10^{-3}



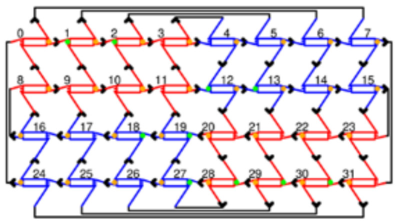
Reservoir: BER < 10^{-5}

0 errors in 131072 bits





Same number of copies as the reservoir has nodes



ACCESSING PHOTONIC CHIP TECHNOLOGIES?

imec

VARY LARGE SCALE (INTEGRATION)

TSMC Fab 14
1.4M 300mm wafers / year

Source: TSMC

SILICON PHOTONICS AND CMOS

The **STRENGTH** of Silicon Photonics

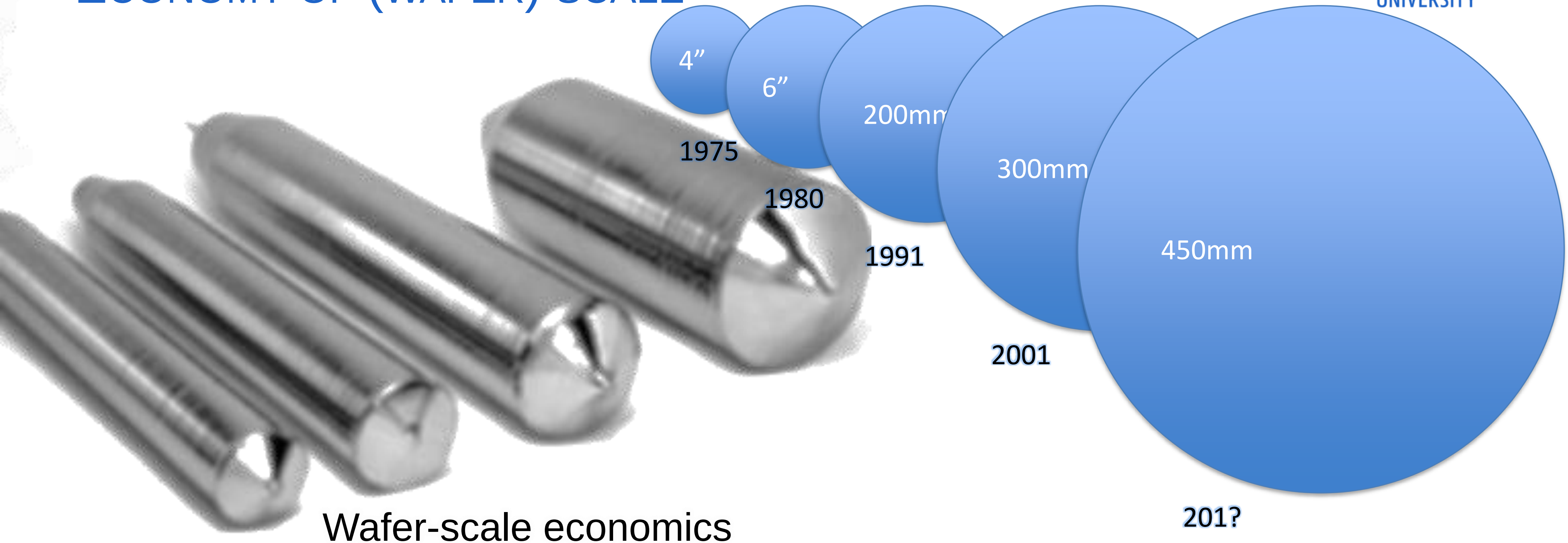
is that it can make use of CMOS-technology

The **WEAKNESS** of Silicon Photonics

is that it **must** make use of CMOS-technology

CMOS-technology requires insanely expensive infrastructure
but delivers ridiculously cheap chips
with a ludicrous degree of sophistication

ECONOMY OF (WAFER) SCALE



Wafer-scale economics

- Larger wafers
- Higher volumes
- Massive parallellism
- Minimal marginal cost

- More expensive tools
- Higher volumes
- Larger fixed cost

REUSE OF (ELECTRONICS) TECHNOLOGY LEVEL

200-300mm fab	huge cost	G$
Process flow development	very large cost	10-50 M$
Fabrication run (25 wafers)	large cost	100K$ - M$
Fabrication run (shared)	moderate cost	10-100K$/user
Chip (high volume)	very low cost	1-100$
Chip (moderate volume)	very low cost	1-100$
Chip (low volume)	low cost	5-500$

WHAT IS HIGH VOLUME?

Saturated 200mm fab

5×5 mm2 per chip
1,250 chips / wafer (200mm)
40,000 wafers / month

50 Mchips / month

2020

~1 fabmonth

Datacenter Cabling

100 mega datacenters
10000 racks / center
64 cables / rack
2 transceivers per cable

128 Mchips

2025

<2 fabyears

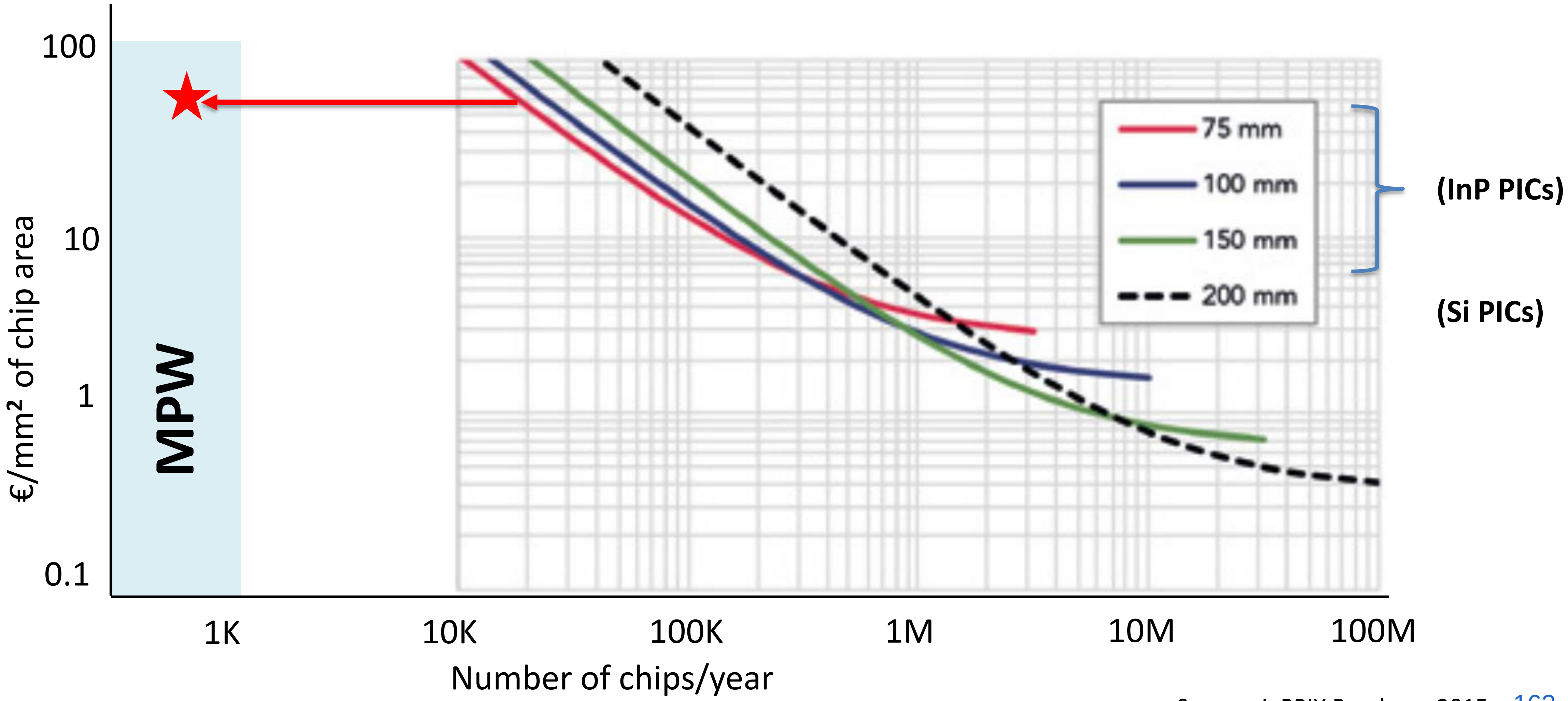
Datacenter Cabling

50 mega datacenters
20000 racks / center
2000 cables / rack
2 transceivers per cable

4 Gchips

ECONOMY OF (WAFER) SCALE

Chip cost per mm² in a dedicated, loaded fab.



Source: JePPIX Roadmap 2015

MULTI-PROJECT-WAFER (MPW) SERVICES

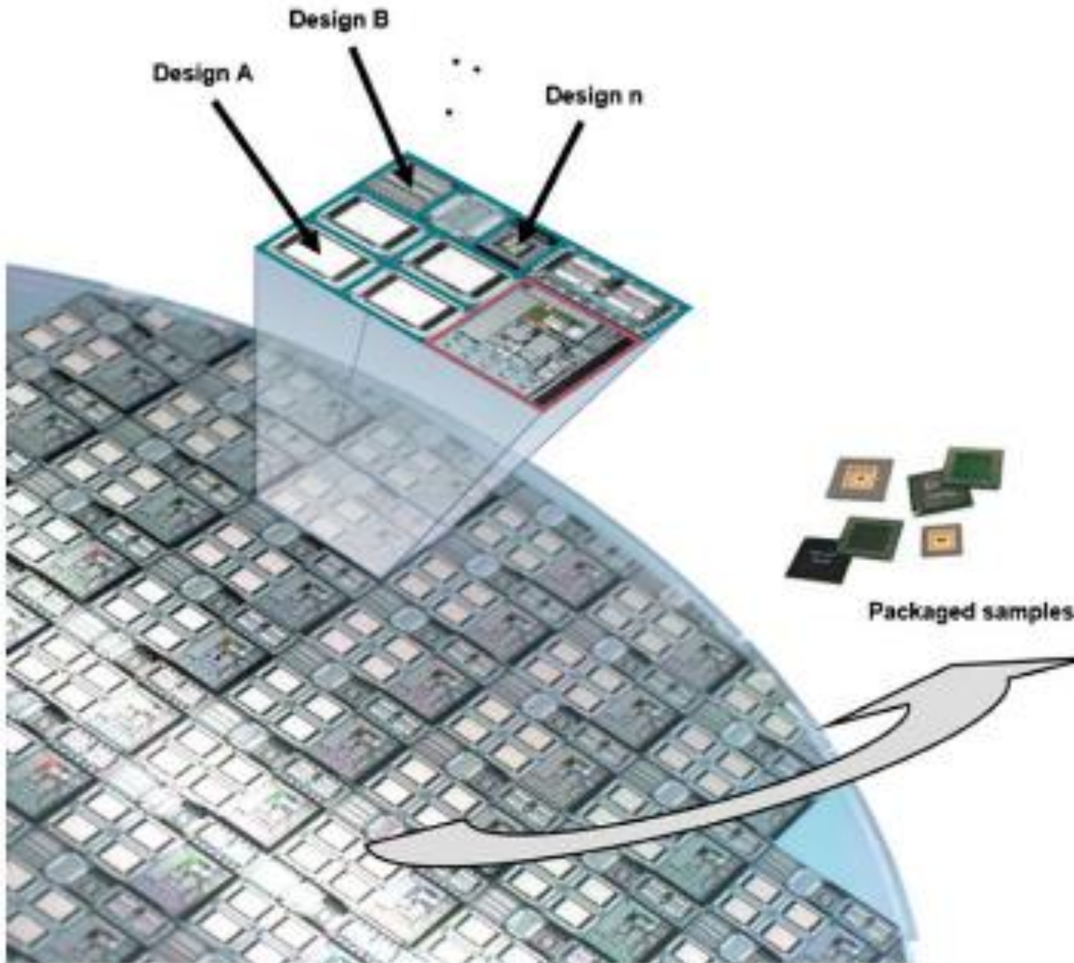
The "reticle" (mask) has an area of ~25 x 25 mm.

That equals 25 chips of 5x5 mm^2

On a 200 (300) mm wafer you can fit 50 (110) chips

Share this cost!!!

1. Collect 25 designs from different users.
2. Combine these on a single mask set
3. Collectively process the wafers (typically 25 wafers in one batch)
4. Dice the wafers into 5x5 mm chips (!!)
5. Send these 5x5 mm chips to each user



Prototyping a New (Silicon) Photonic IC

Design (4M)

Fabrication (6M)

Package (1M)

Test (2M)

Then you discover the bugs…

Repeat!

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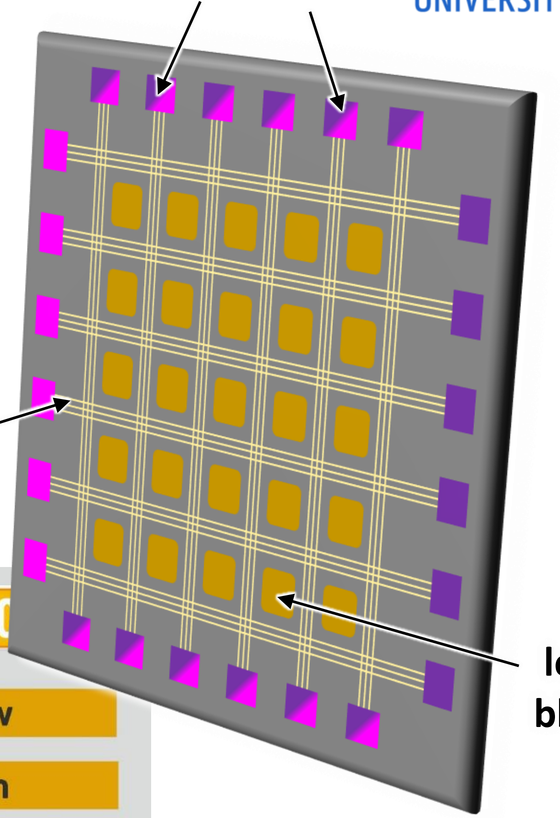
PROTOTYPING A NEW ELECTRONIC CIRCUIT

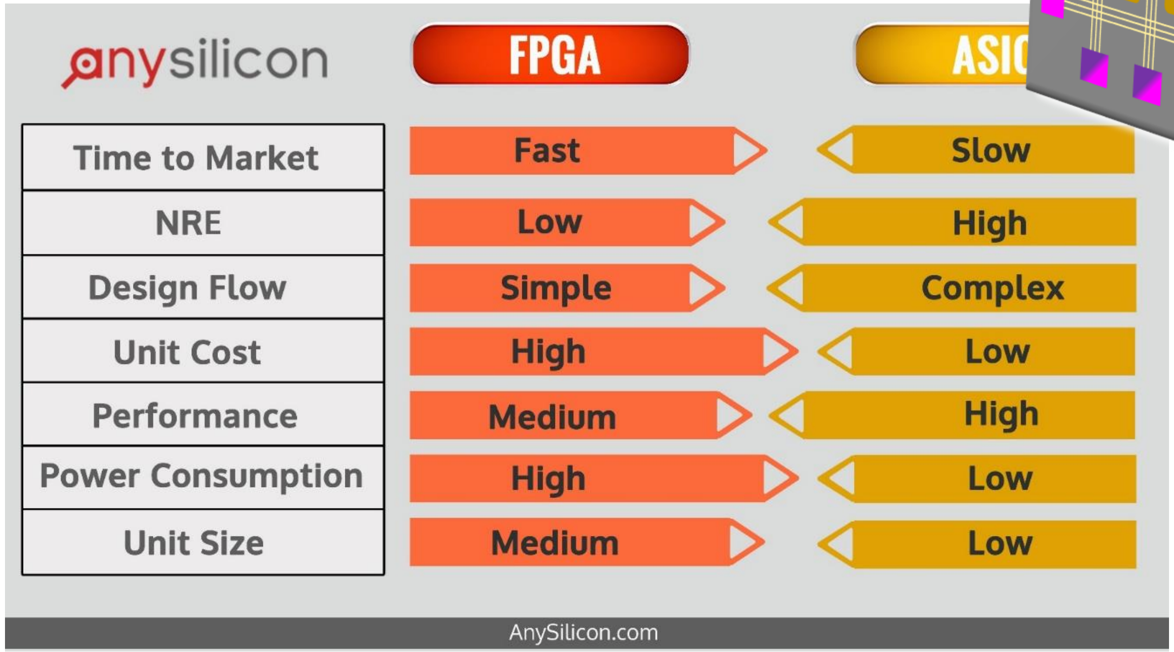
Select a suitable programmable IC: FPGA, DSP, µC (1d)

Program and test the chip (1-4w)

Only then, if needed:

- Design ASIC …

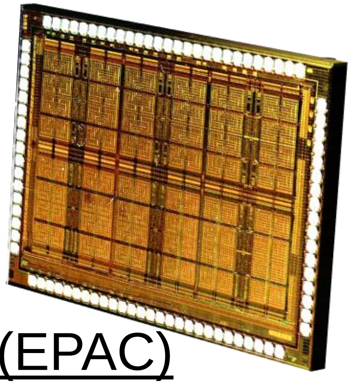




	FPGA	ASIC
Time to Market	Fast	Slow
NRE	Low	High
Design Flow	Simple	Complex
Unit Cost	High	Low
Performance	Medium	High
Power Consumption	High	Low
Unit Size	Medium	Low

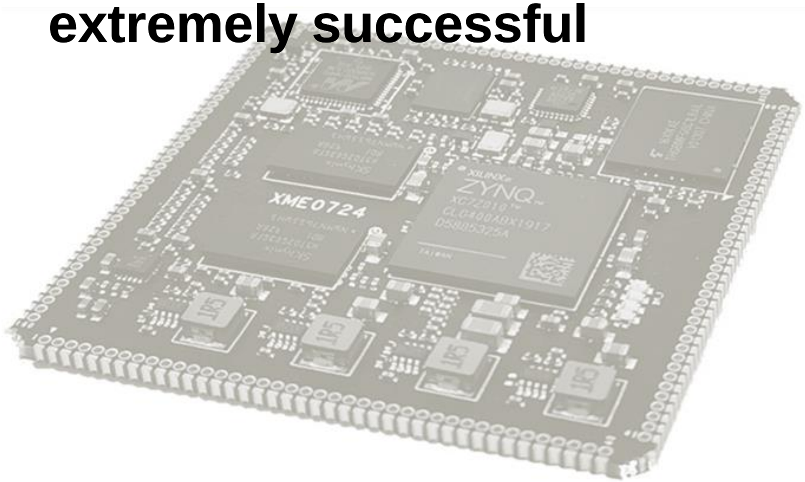
AnySilicon.com

FPGA, FPAA, EPAC, RASP



Field-Programmable Gate Array (FPGA)

- **digitally** (configurable) logic blocks
- programmable interconnections
- high performance
- **extremely successful**

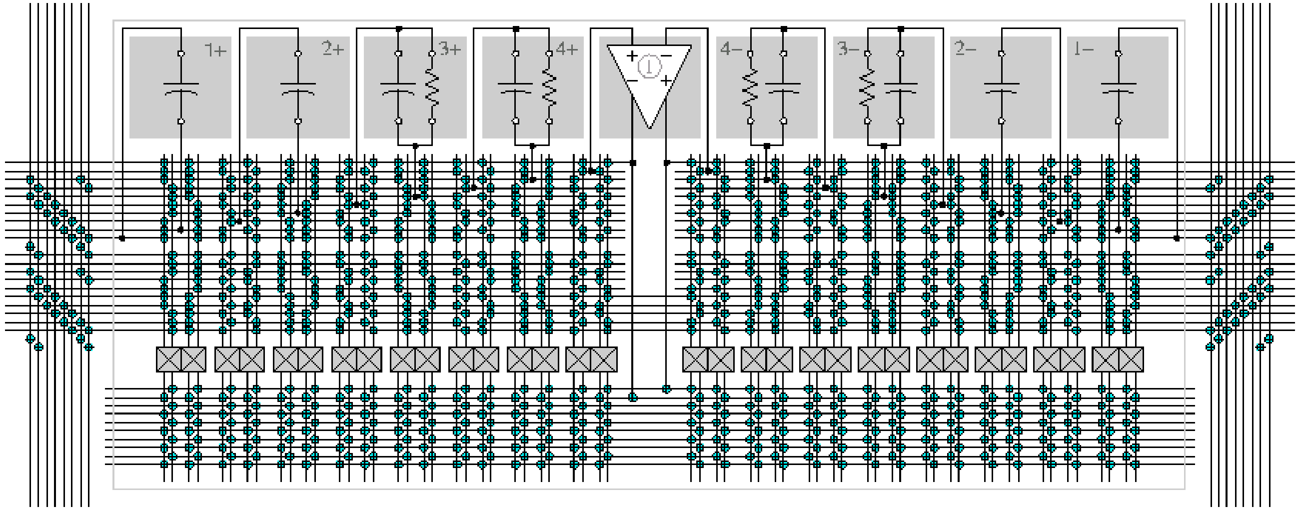


Field-Programmable Analog Array (FPPA)

Electronically Programmable Analog Circuits (EPAC)

Reconfigurable Analog Signal Processor (RASP)

- **analog** opamps and passives
- programmed through **digital** switches
- signal integrators, filters, vector-matrix multipliers
- limited processing power, **bandwidth** (< MHz)



The Photonic FPGAs?

or programmable photonics

reconfigurable photonics

photonic processors

universal photonic circuits …

analog optical functions

digitally programmed

high **bandwidth** (microwaves)

extremely successful

Photonic Integrated Circuits

that **can be reconfigured**

using **software**

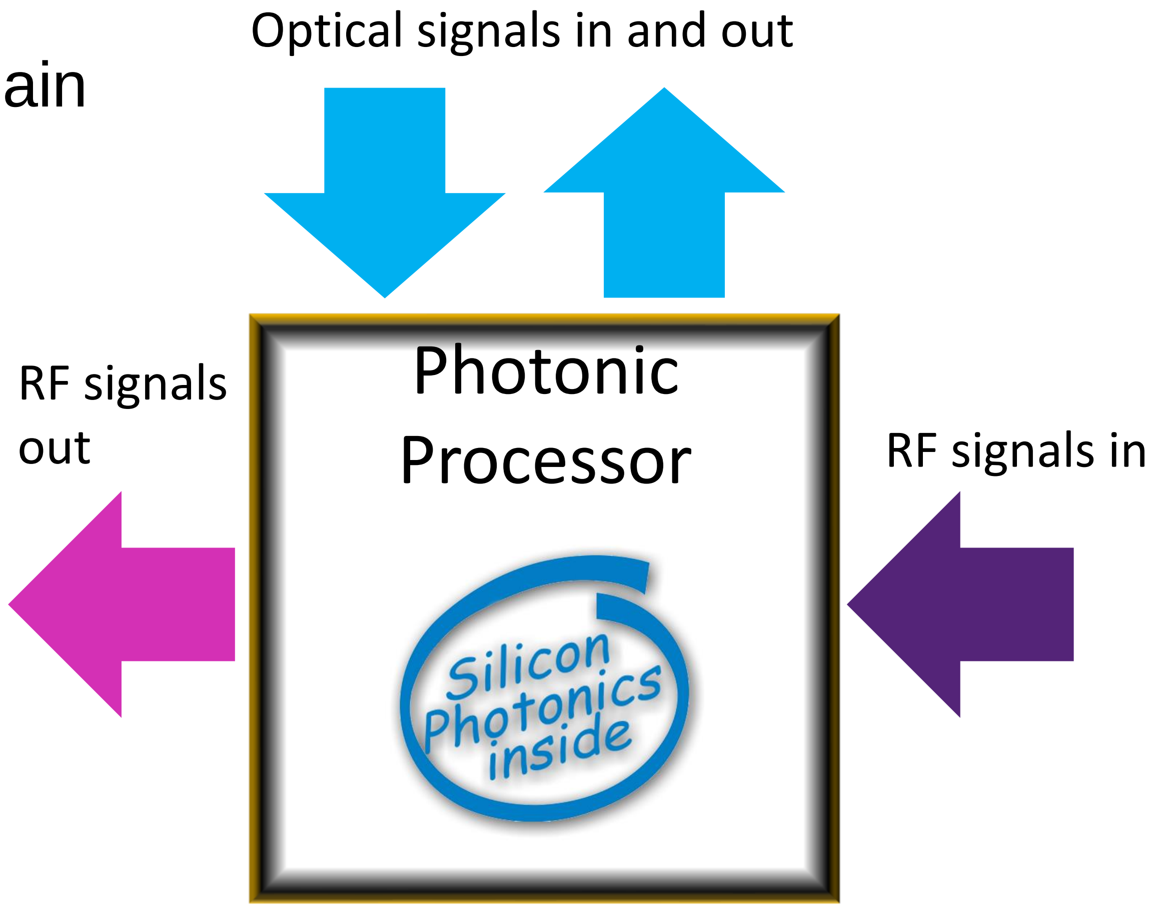
to perform **different functions**.

Programmable Photonic Chip

Can process signals in the optical domain

- balancing
- filtering
- transformations

Both on Optical and RF signals



GENERIC PROGRAMMABLE OPTICAL PROCESSOR

Optical inputs and outputs

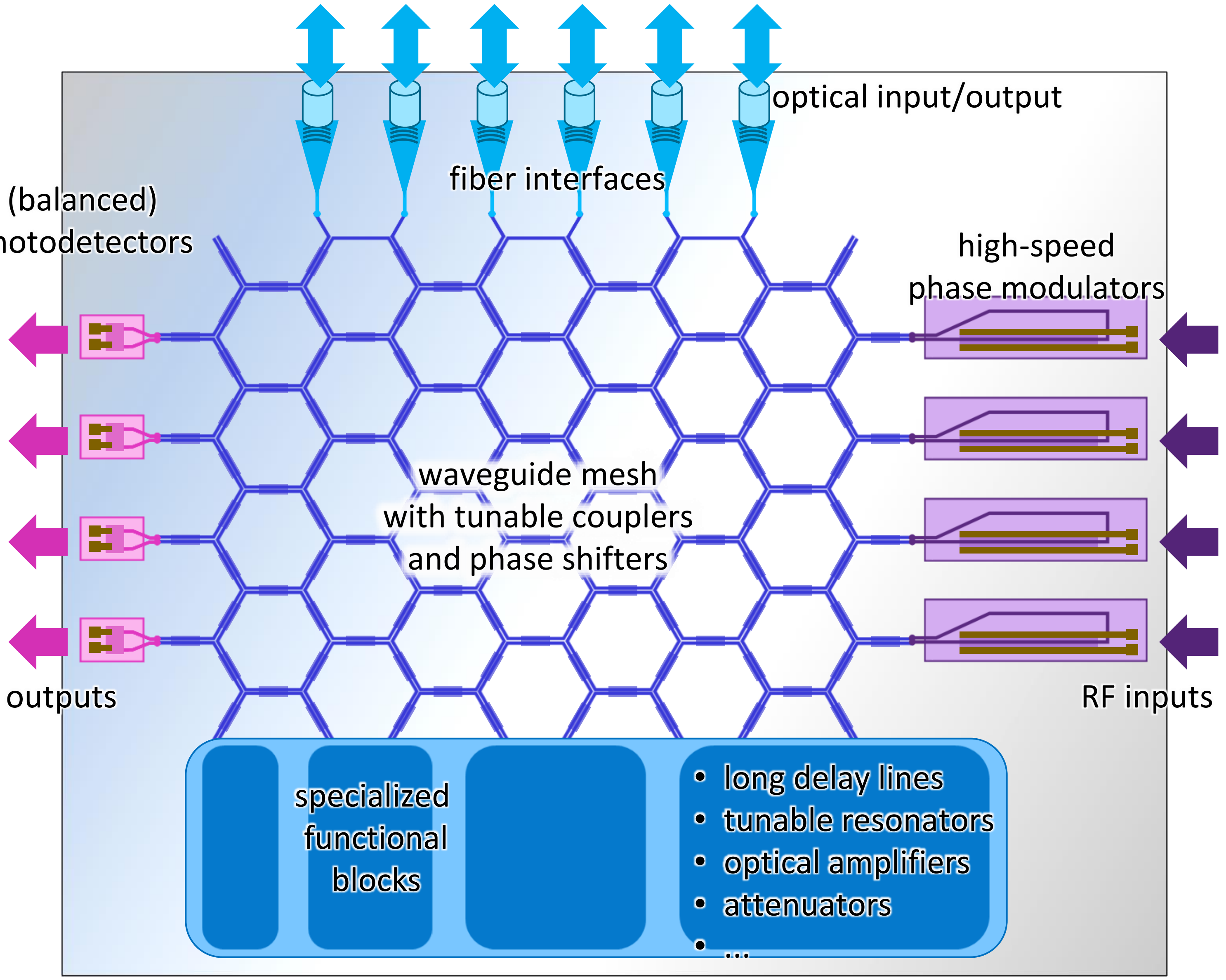
RF inputs: modulators

RF outputs: balanced PDs

Specialized high performance blocks

Connected by a programmable

linear optical circuit

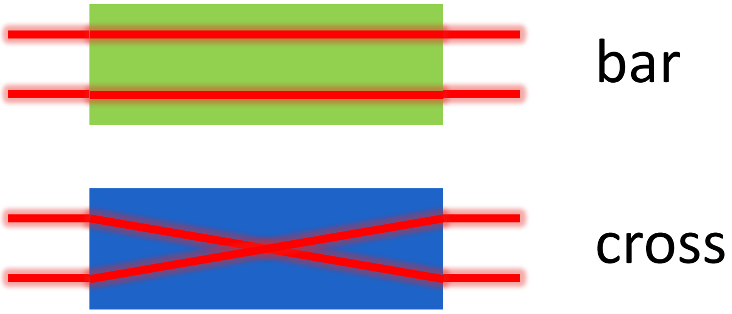


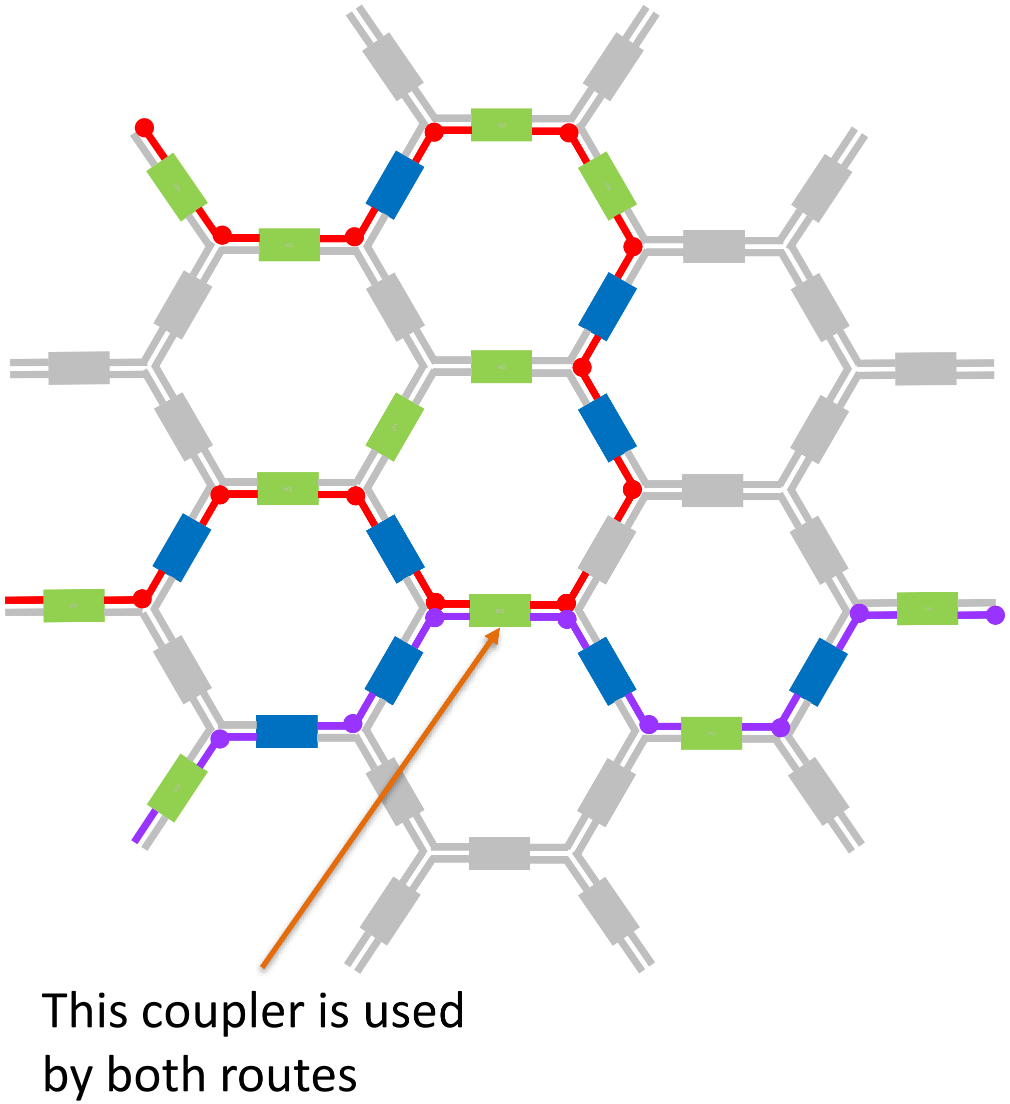
(RE)ROUTING LIGHT

Light can be arbitrarily routed

Multiple routes in the same mesh

Edges can be shared



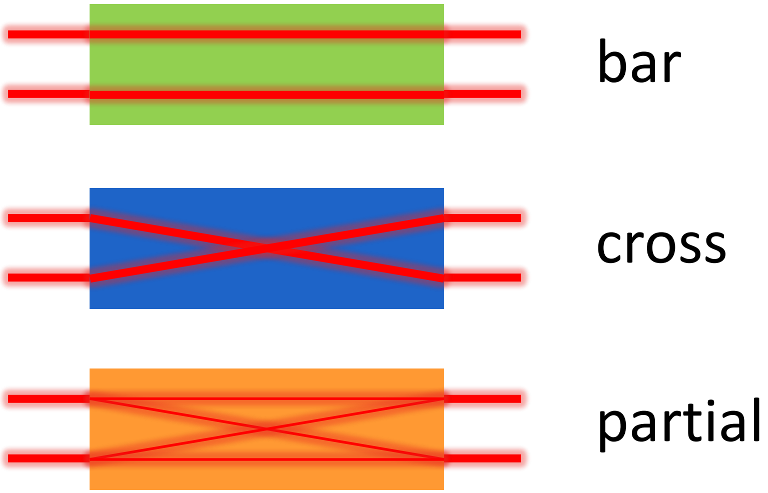


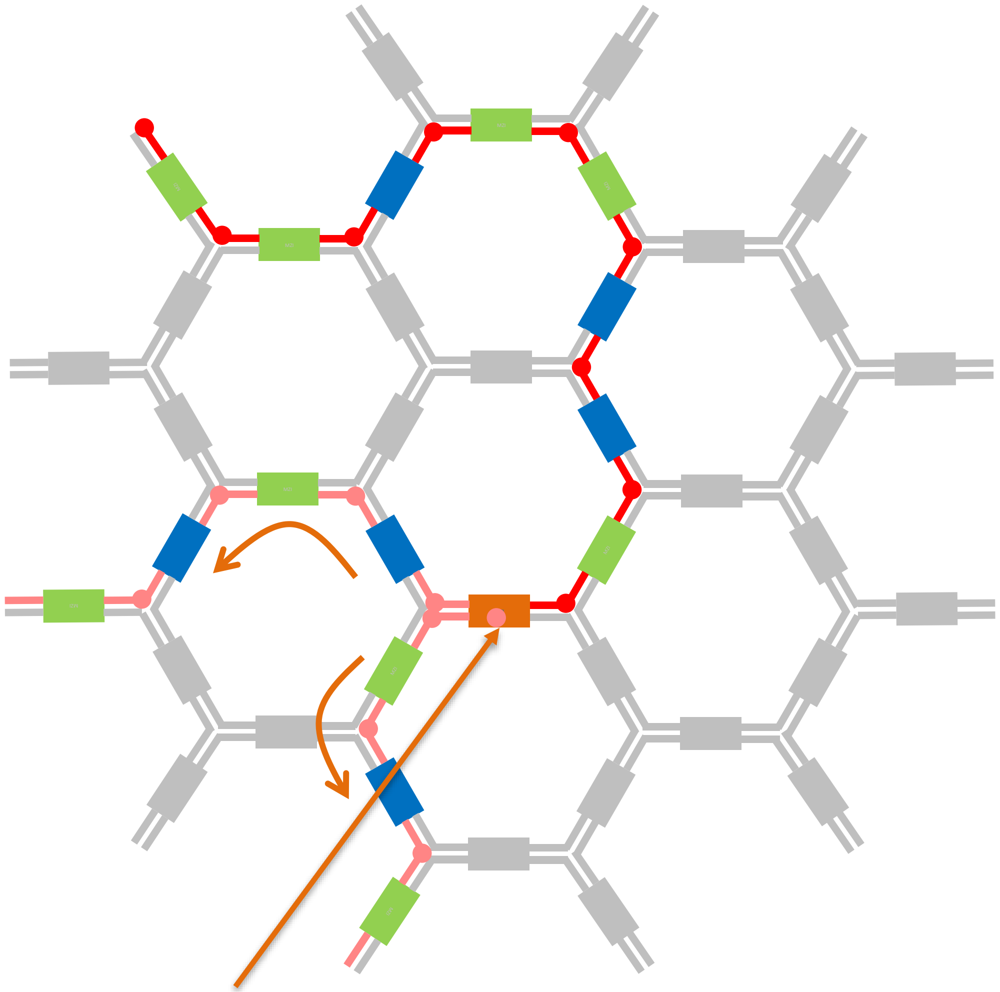
SPLITTING LIGHT

Couplers control arbitrary splitting ratios

Power distribution networks

Multicasting



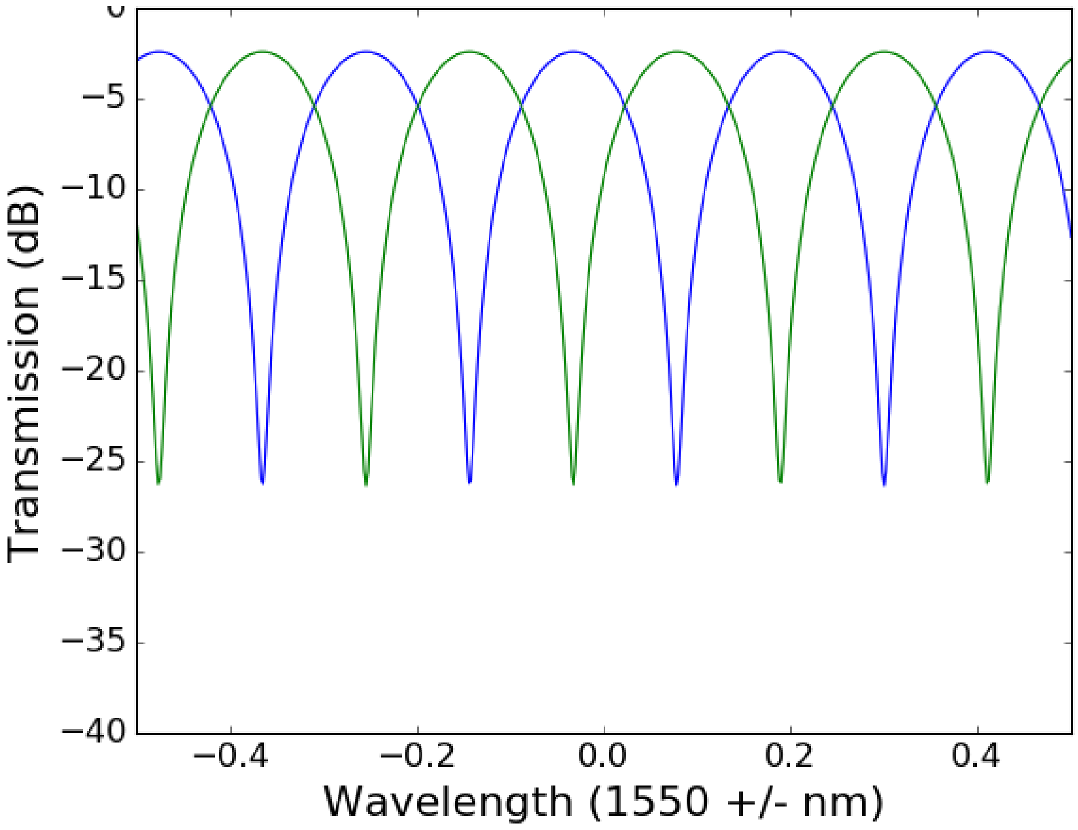


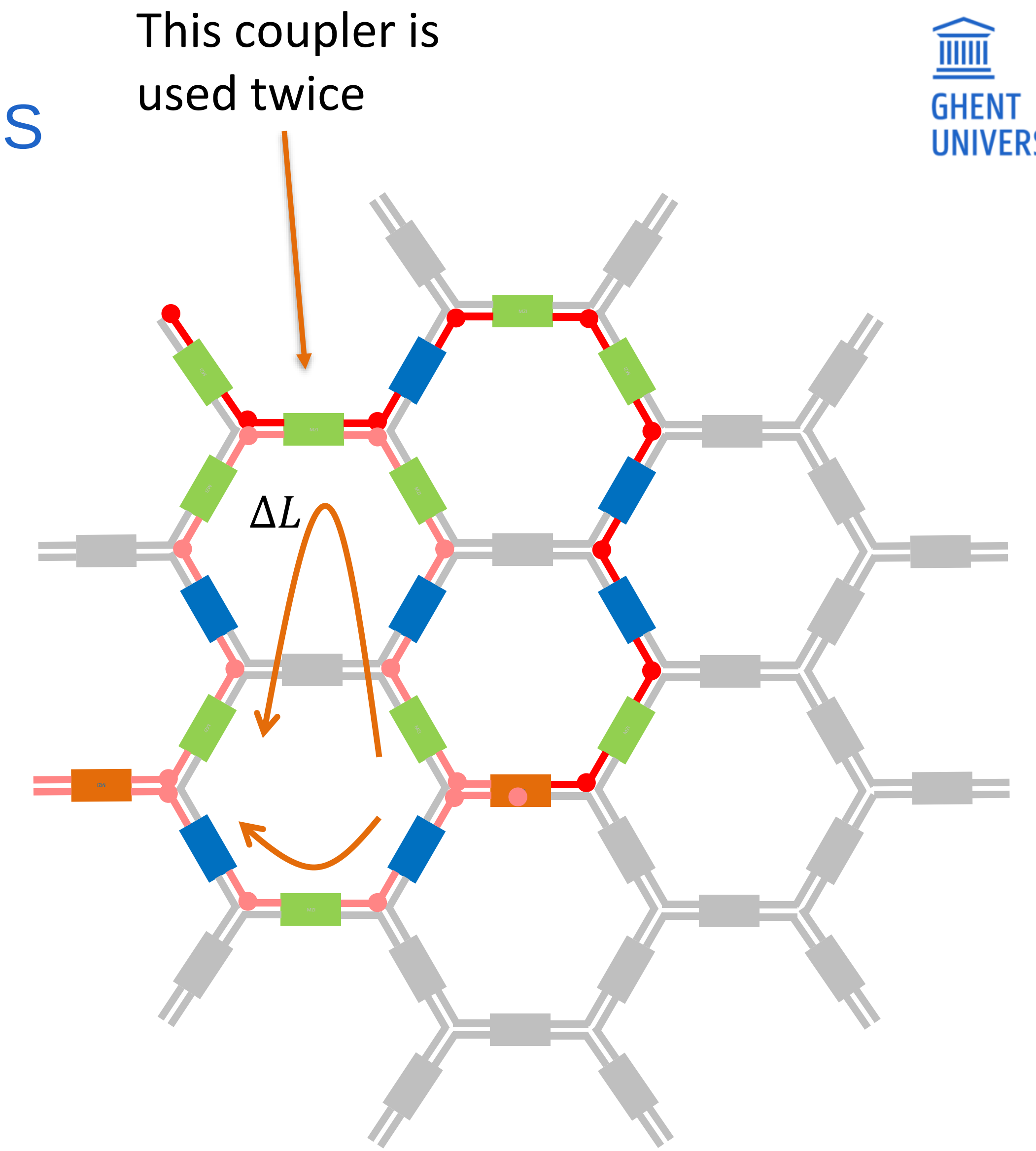
This coupler acts as a splitter

MACH-ZEHNDER INTERFEROMETERS

Basic building block for FIR filters

Delay can be adjusted per unit lengths

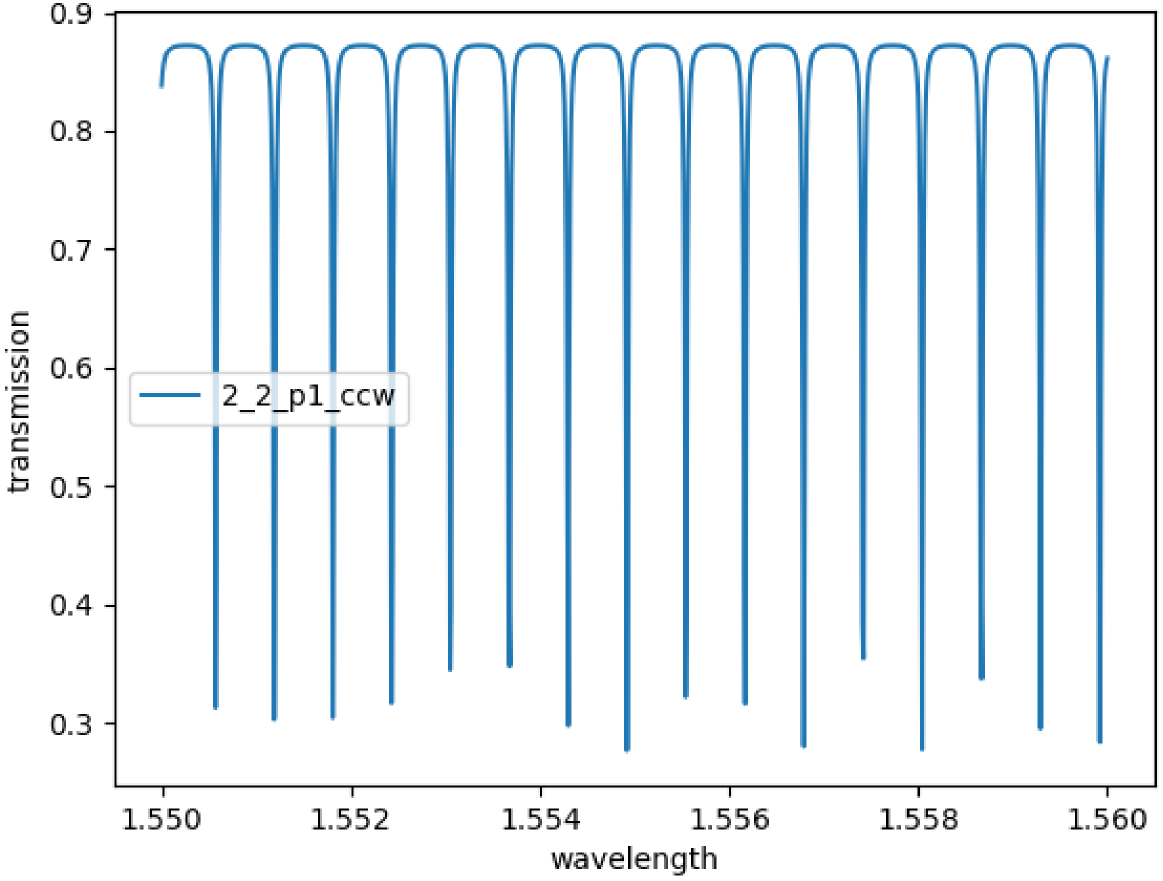


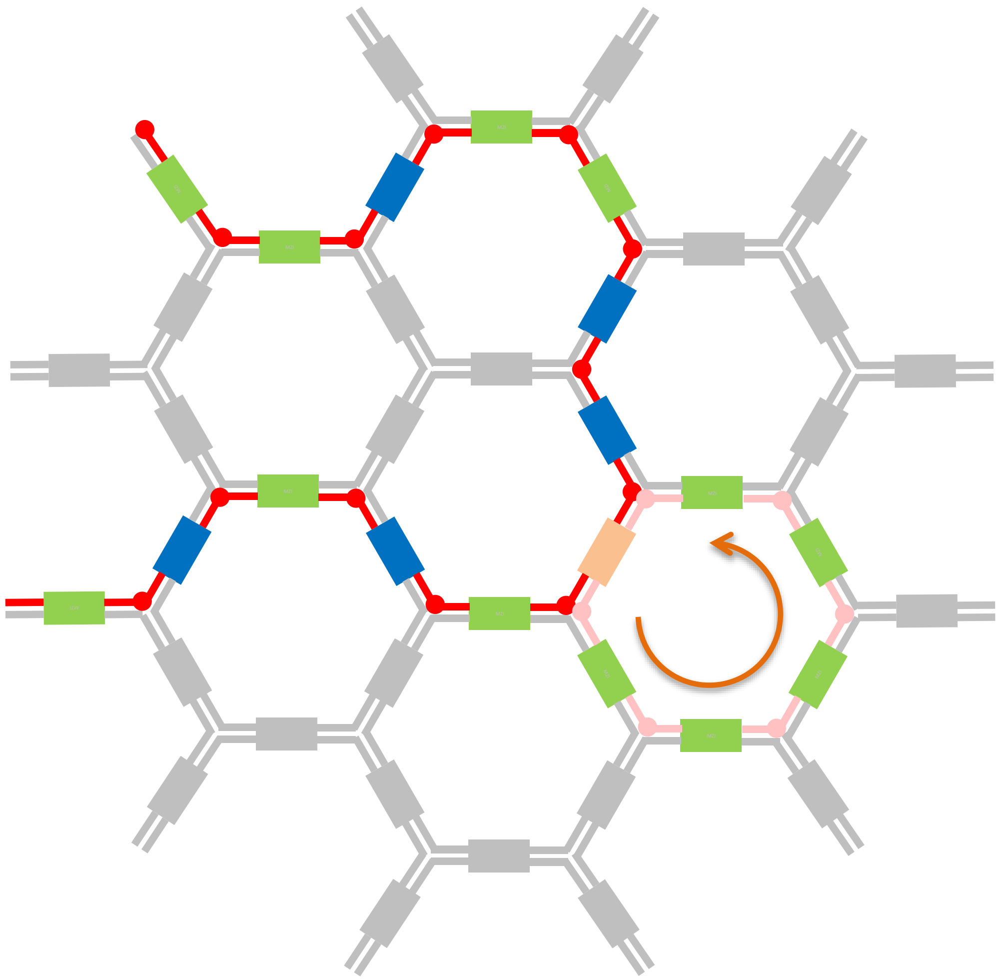


RING RESONATORS

Loop light in itself

Coupler ring resonators together

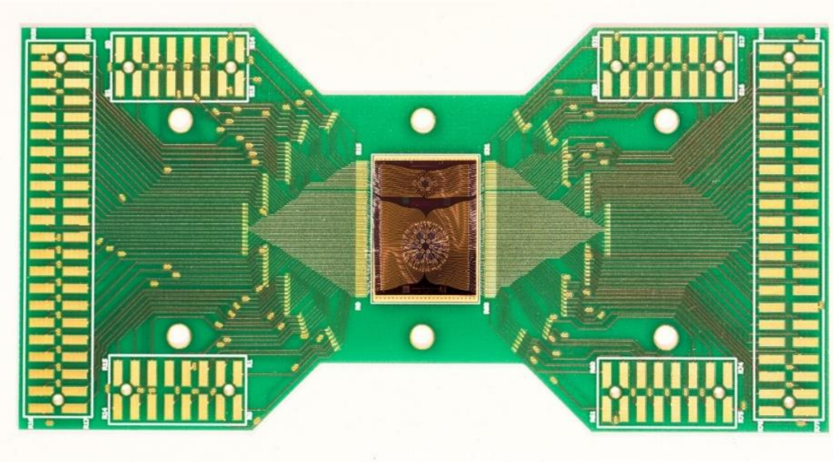


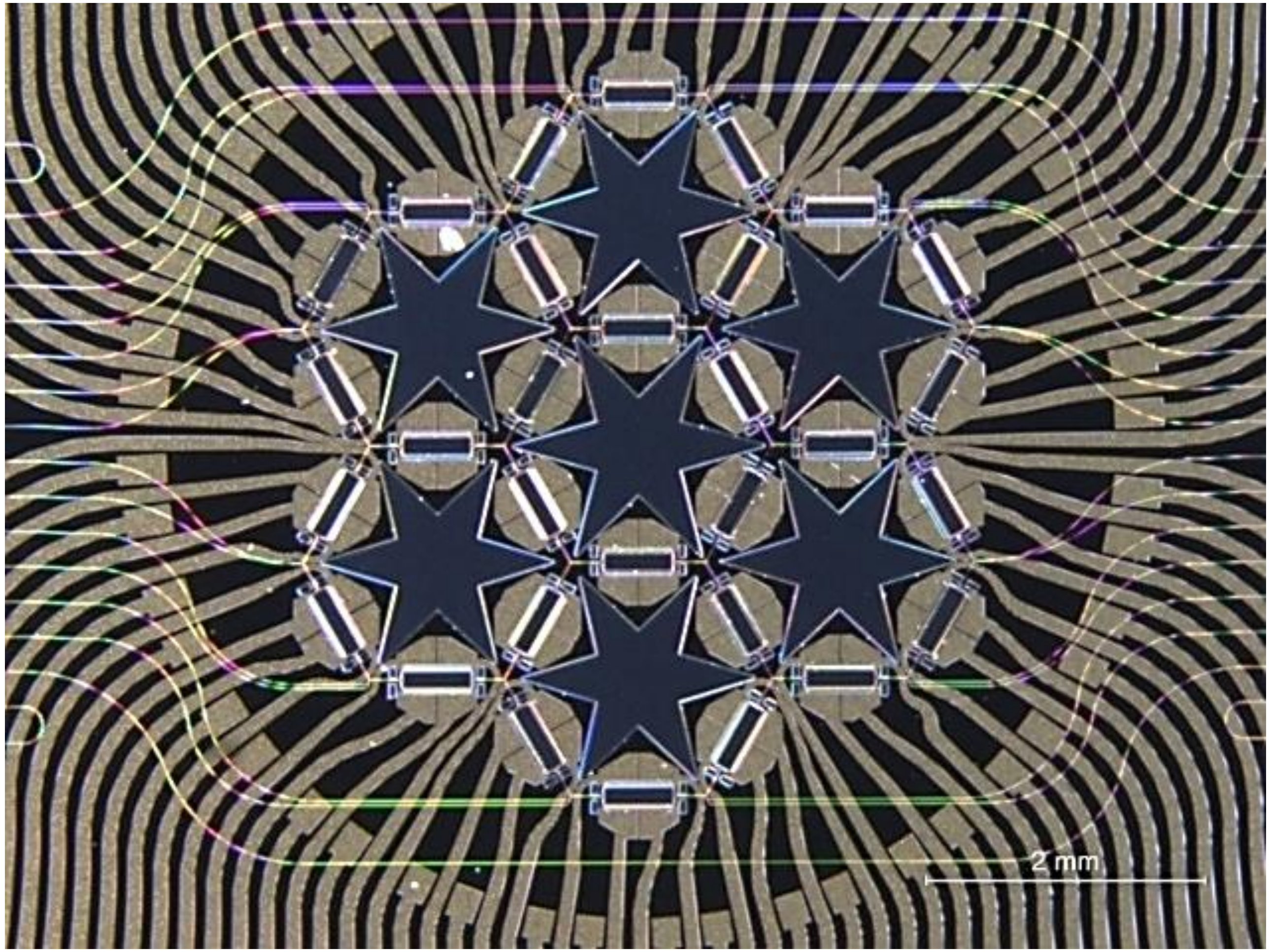


HEXAGONAL MESH CIRCUIT DEMONSTRATION

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

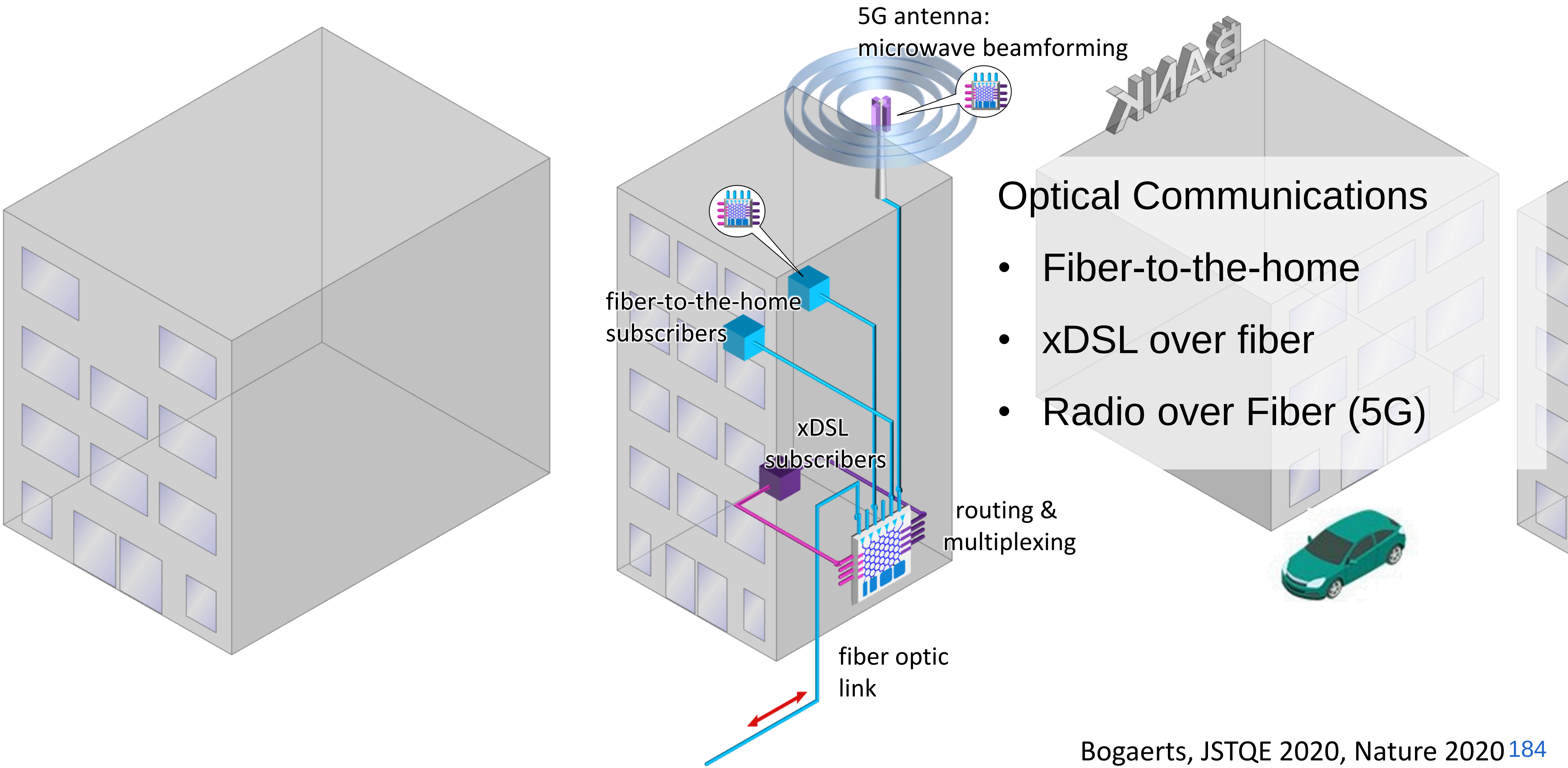
- 7 hexagonal cores
- 30 tunable couplers
  (2 heaters per coupler)
- >100 possible circuits





Perez et al, Nature Comm. 2017

Programmable Photonics can be used in many places



Optical Communications

- Fiber-to-the-home
- xDSL over fiber
- Radio over Fiber (5G)

Bogaerts, JSTQE 2020, Nature 2020

PROGRAMMABLE PHOTONICS CAN BE USED IN MANY PLACES

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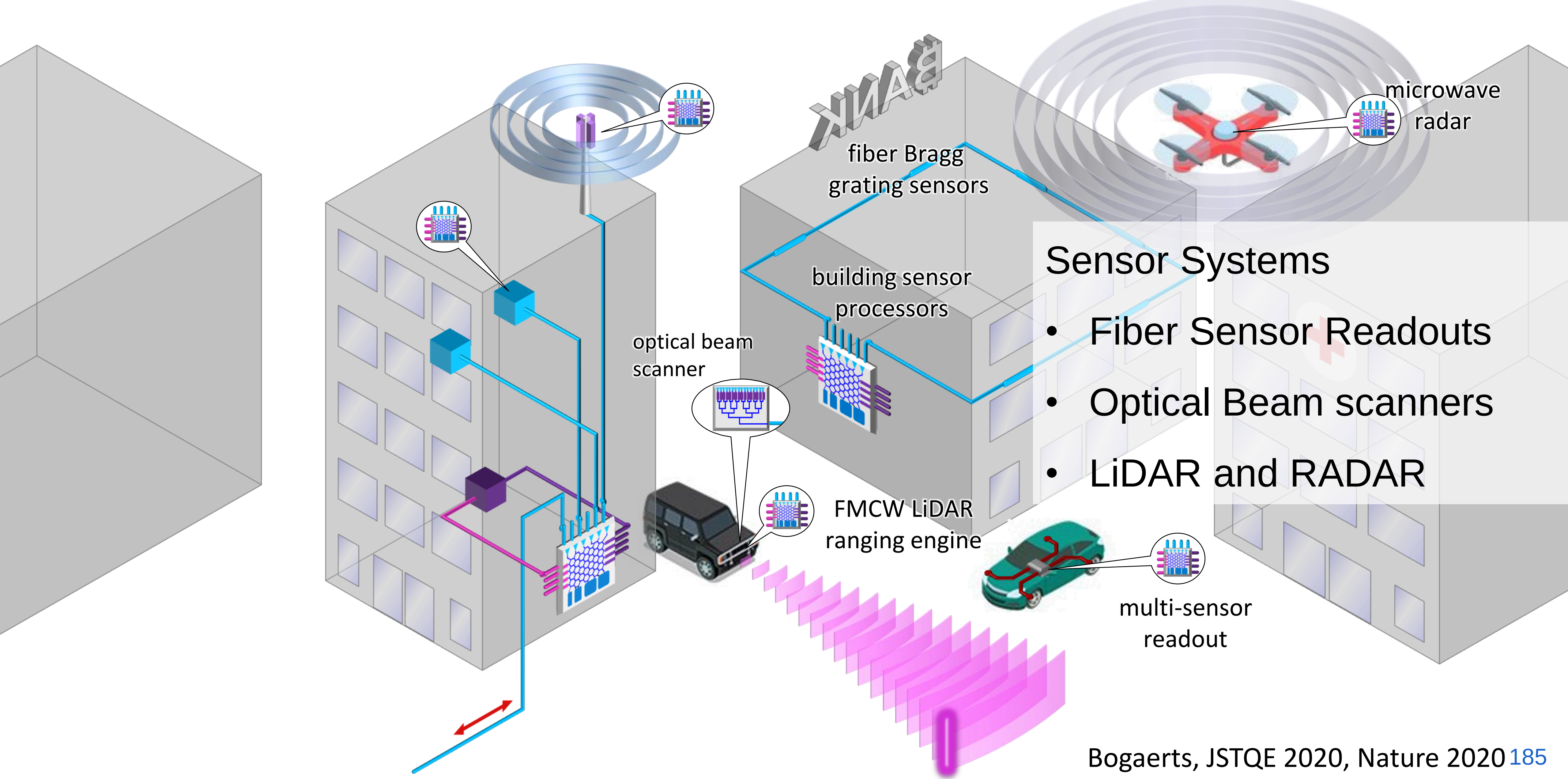


Sensor Systems

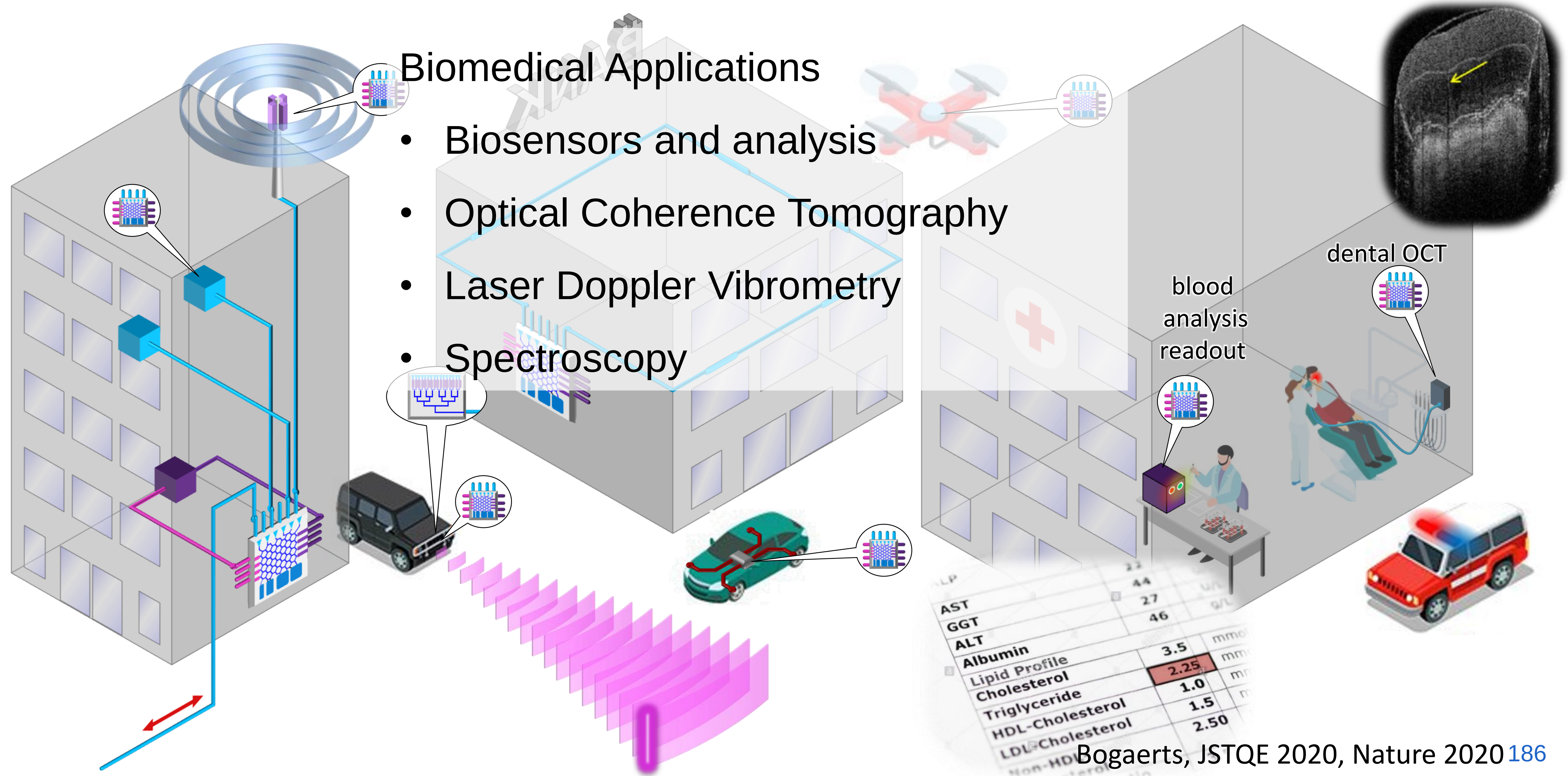
- Fiber Sensor Readouts
- Optical Beam scanners
- LiDAR and RADAR

Bogaerts, JSTQE 2020, Nature 2020

Programmable Photonics can be used in many places

Biomedical Applications

- Biosensors and analysis
- Optical Coherence Tomography
- Laser Doppler Vibrometry
- Spectroscopy



Bogaerts, JSTQE 2020, Nature 2020

PROGRAMMABLE PHOTONICS CAN BE USED IN MANY PLACES

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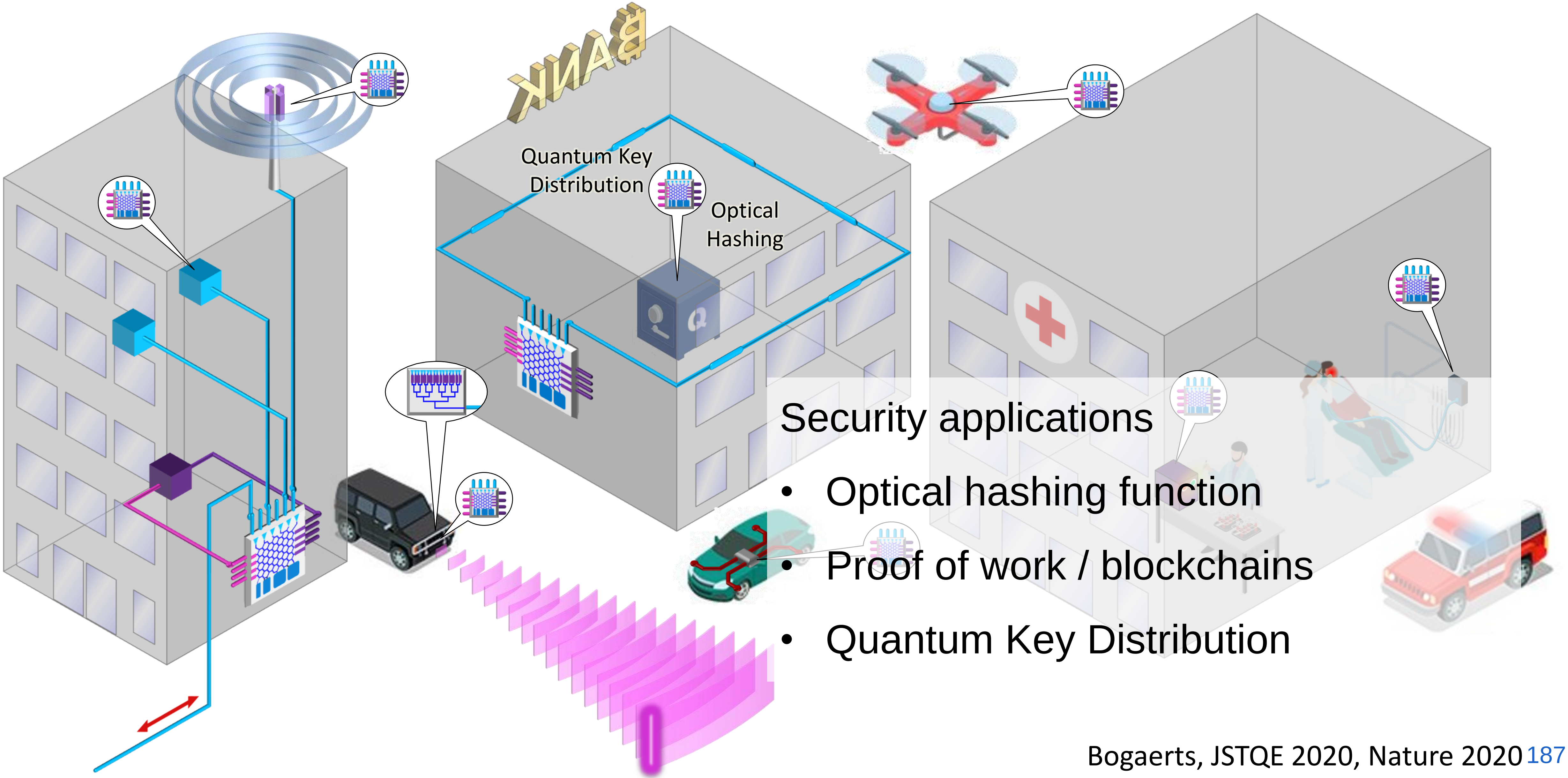


Security applications

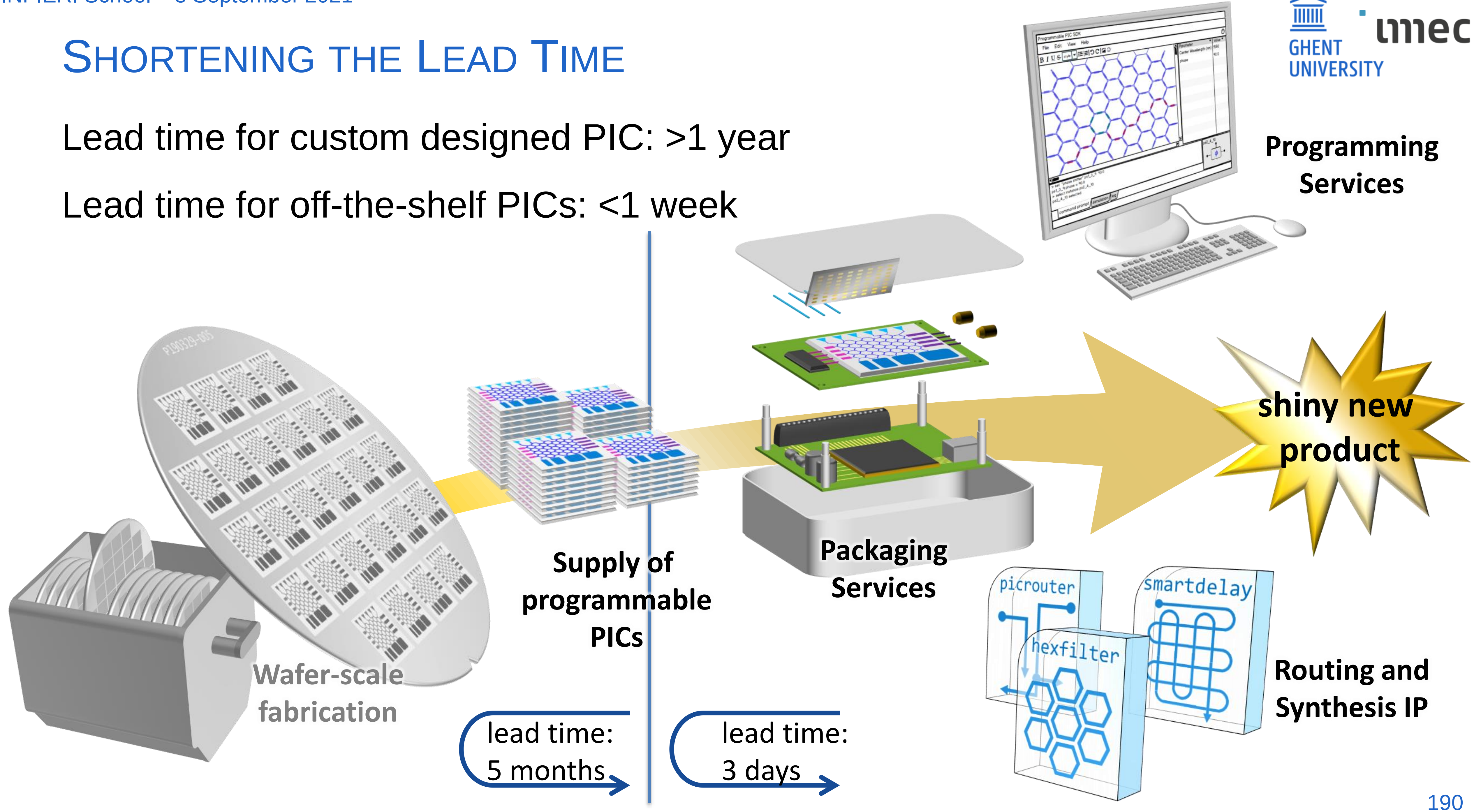
- Optical hashing function
- Proof of work / blockchains
- Quantum Key Distribution

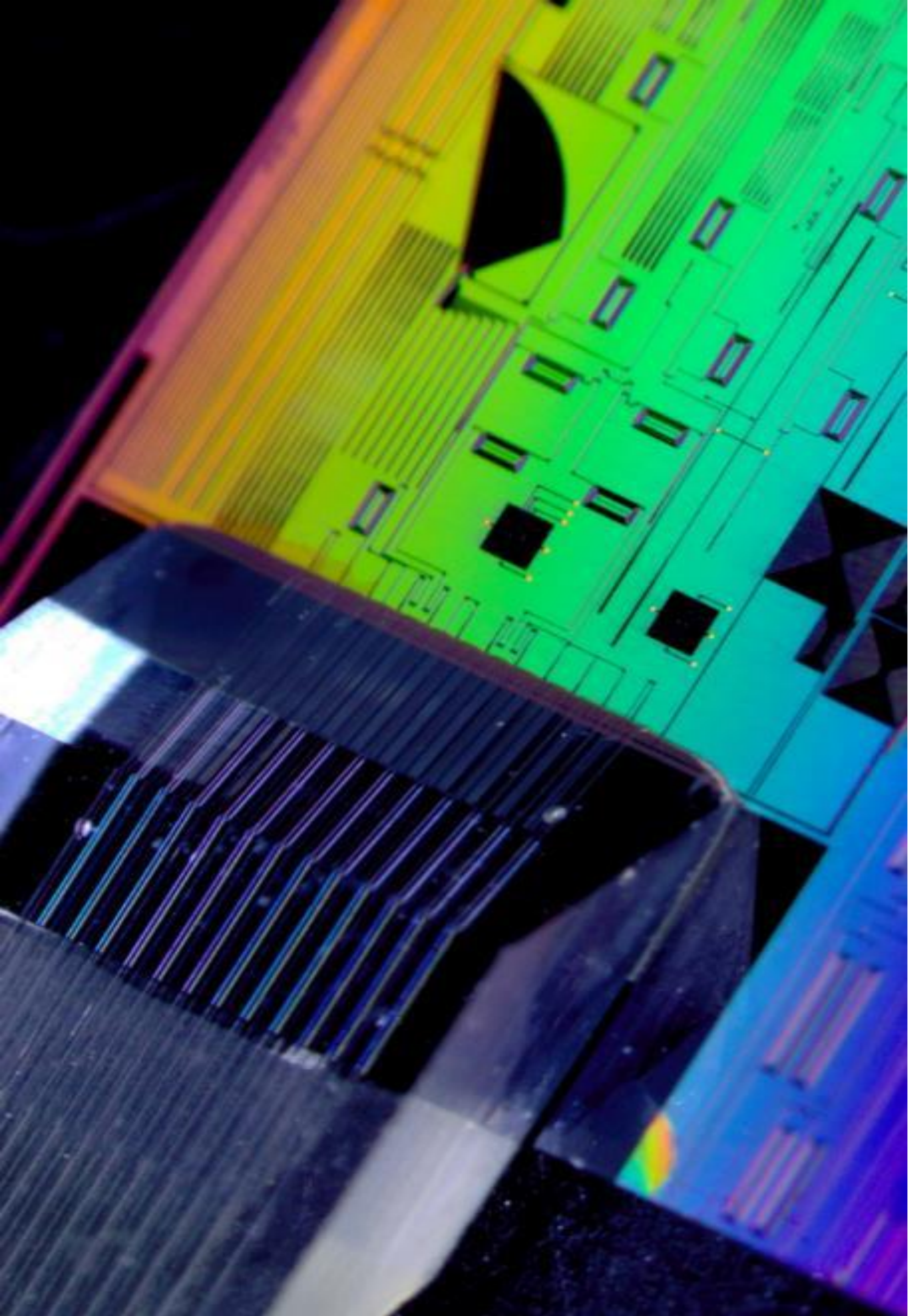
Bogaerts, JSTQE 2020, Nature 2020

Shortening the Lead Time

Lead time for custom designed PIC: >1 year

Lead time for off-the-shelf PICs: <1 week





SUMMARY

Photonic Integrated Circuits:

manipulating light on a chip

benefits in performance, SWaP

Silicon: Rapidly maturing chip technology

(using industrial fabs)

Wide range of applications

- communications
- sensing
- computing
- …

PHOTONICS RESEARCH GROUP

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