Karlsruhe Institute of Technology

Silicon Photonics

Institute for Data Processing and Electronics

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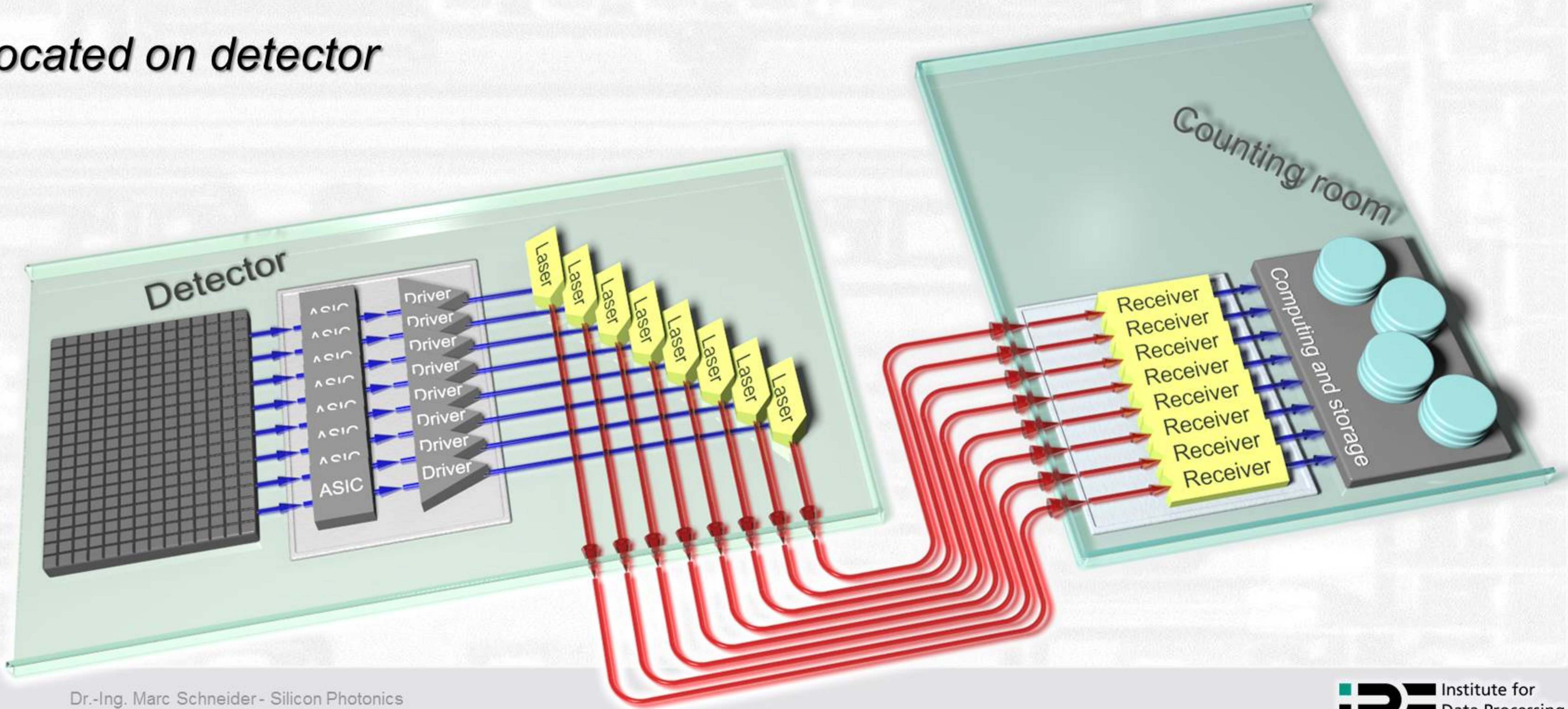
CNRS School, Fréjus, France

2018-11-12

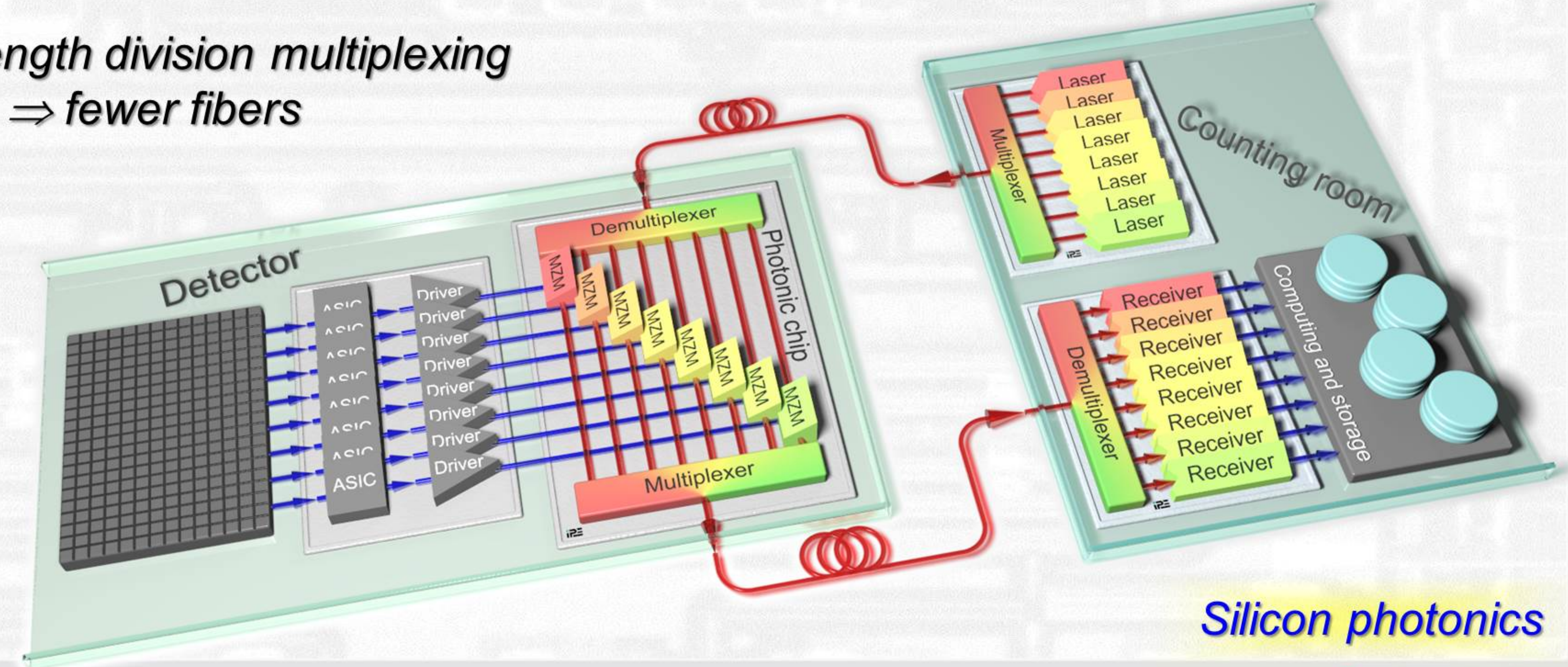
State of the Art

- 15000 optical fibers for CMS tracker, ≤ 5 Gb/s per fiber
- Only a fraction of data is read out
- Lasers located on detector



Read out ALL data?

- *Efficient and radiation-hard modulators*
- *Lasers located off detector*
- *Wavelength division multiplexing (WDM) ⇒ fewer fibers*



Silicon photonics

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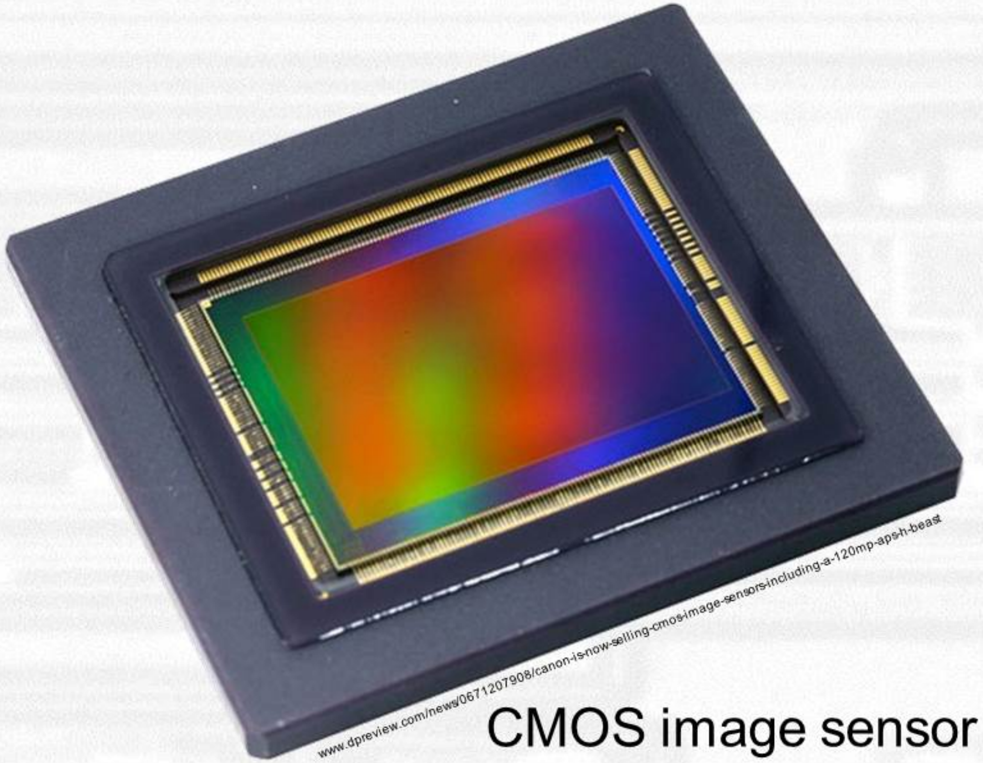
Silicon Photonics?

A definition:

- *Silicon Photonics studies the generation, transmission, modulation, processing, and detection of light using silicon as the optical medium.*



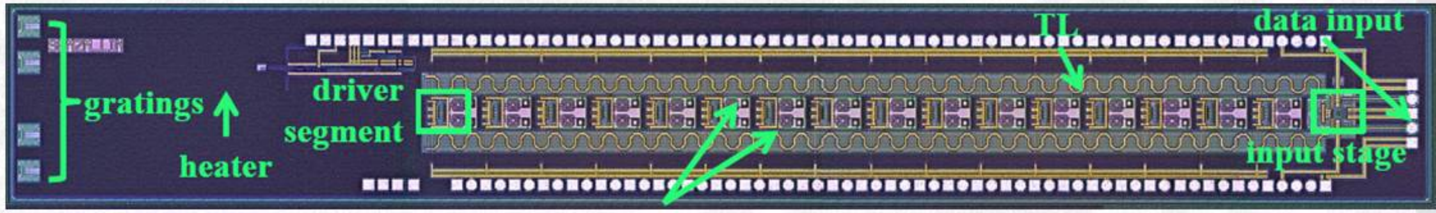
CMOS image sensor

Shutterstock

Solar cells

Silicon Photonics

- Cheap
- Fast devices
- Integrates with electronics
- Can be made radiation hard
- Efficient devices

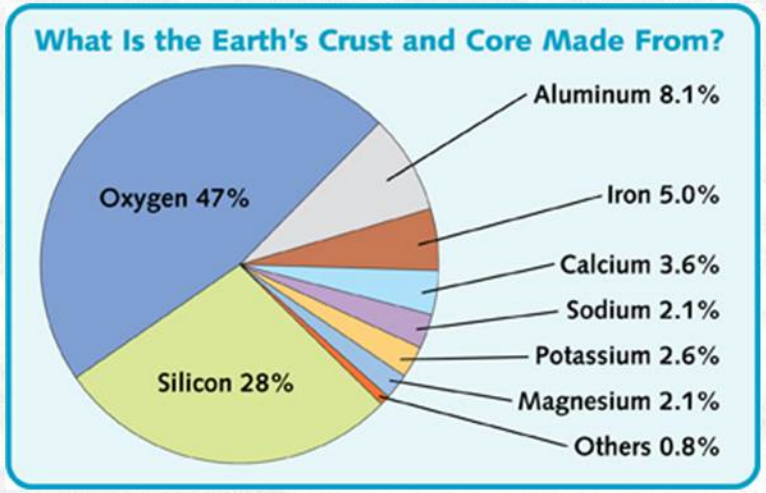


https://dimension-h2020.eu/wp-content/uploads/Petousi_PTL2016.pdf

…but let's start at the beginning

Silicon

- *Eighth most common element in the universe by mass and second most on earth (after oxygen)*
- *First prepared in almost pure form 1811 by Joseph Louis Gay-Lussac and Louis Jacques Thénard, in pure form 1824 by Jöns Jakob Berzelius in Sweden*



science.jrank.org/kids/pages/212/Common-Elements.html

Wikimedia Commons

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Silicon

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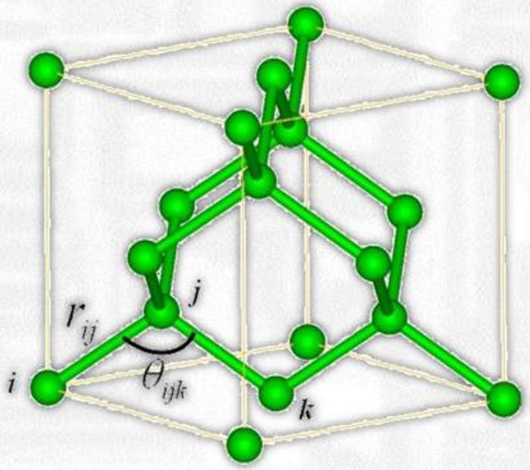
- *Atomic number: 14*
- *Structure: face-centered diamond-cubic*
- *Band gap: 1.12 eV, indirect*
- *Transparent to infrared light above 1.1 µm*
- *Refractive index: ≈3.476 @1550 nm, 293 K*
- *Semiconductor purity: 99.9999999% Si, nearly defect free single crystal*

Wikipedia



https://www.researchgate.net/publication/252513197_Molecular_dynamics_simulation_of_heat_transport_across_silicon-carbon_nanotubes_interface/figures?lo=1

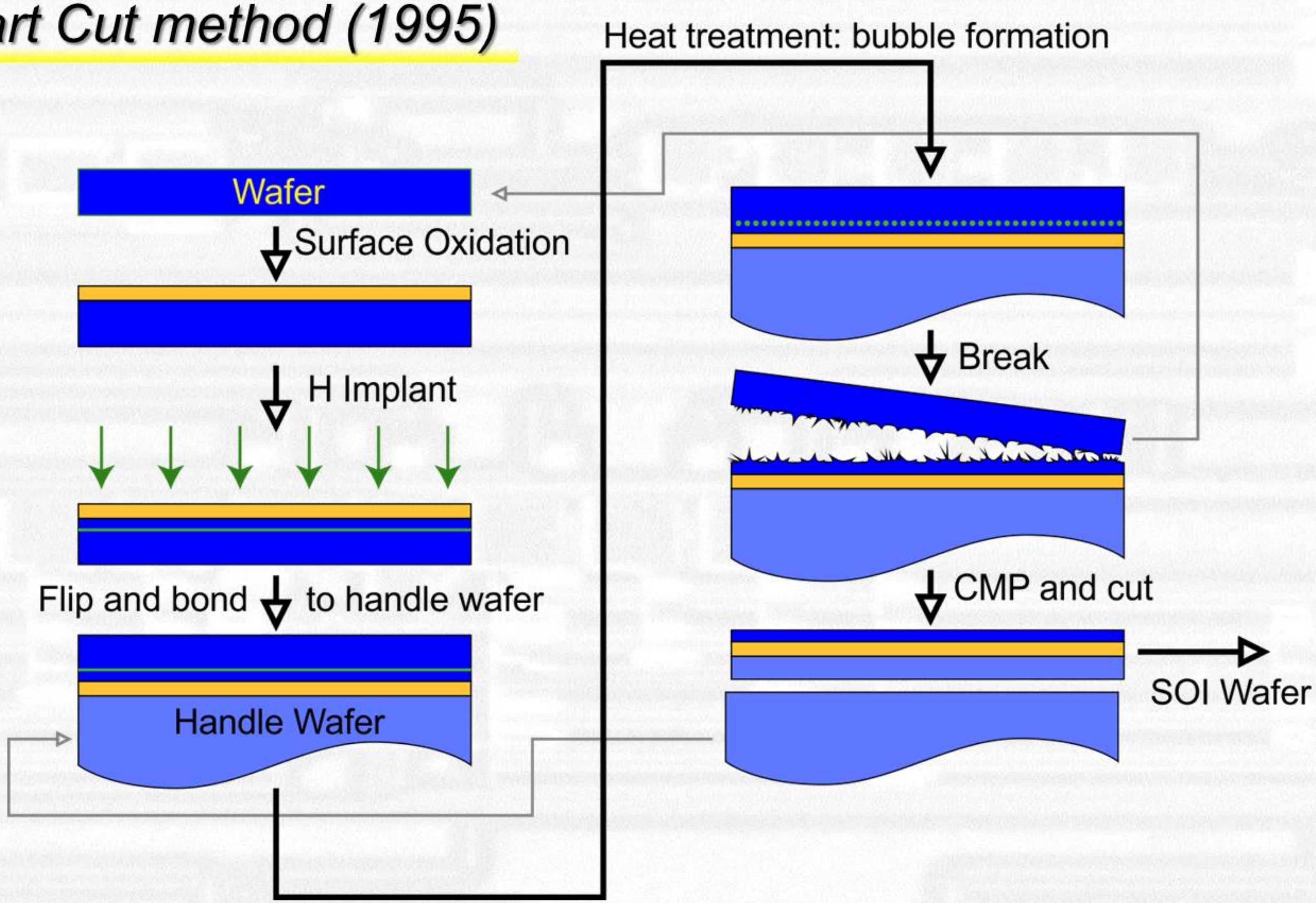
Silicon

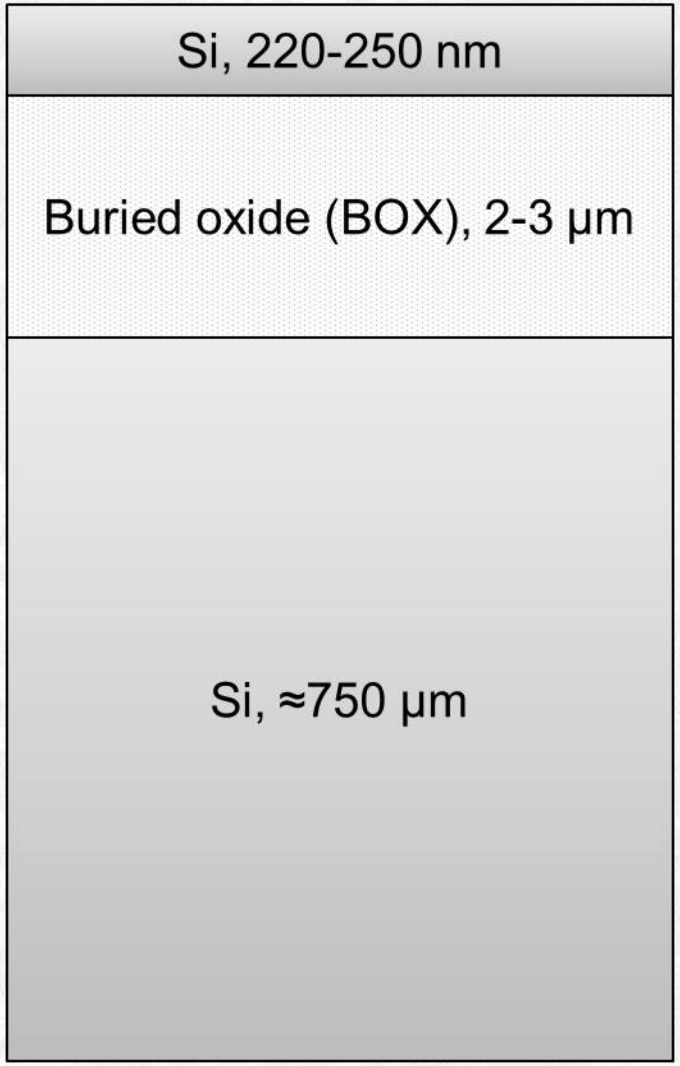
- High quality native oxide: SiO_2
  - Relative low refractive index: 1.45 @1550 nm
  - Transparent at telecom wavelengths
  - ➔ Good silicon waveguide cladding material
- High Si-SiO_2 index contrast $\Rightarrow$ compact devices
- ➔ Common platform: Silicon-on-Insulator (SOI) for integrated optics
  OEIC: opto-electronic integrated circuit or
  PIC: photonic integrated circuit

Wikipedia

Silicon-on-Insulator: Wafers (since 1988)

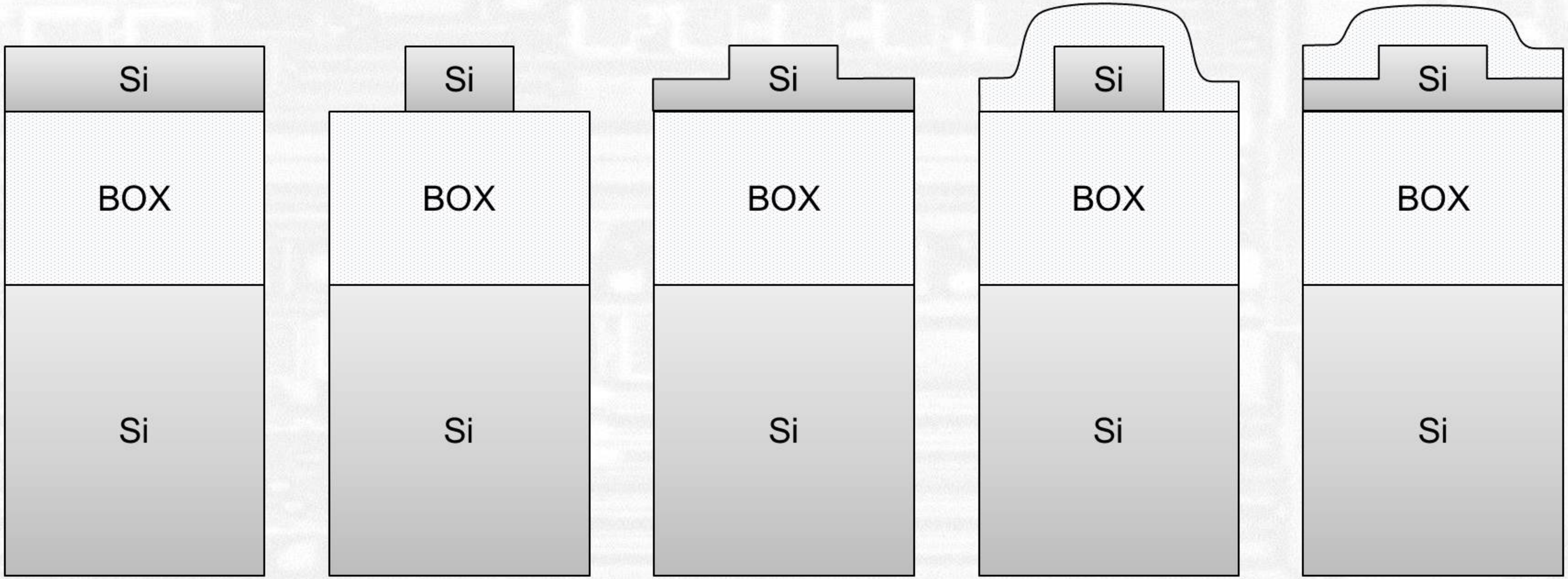
Smart Cut method (1995)



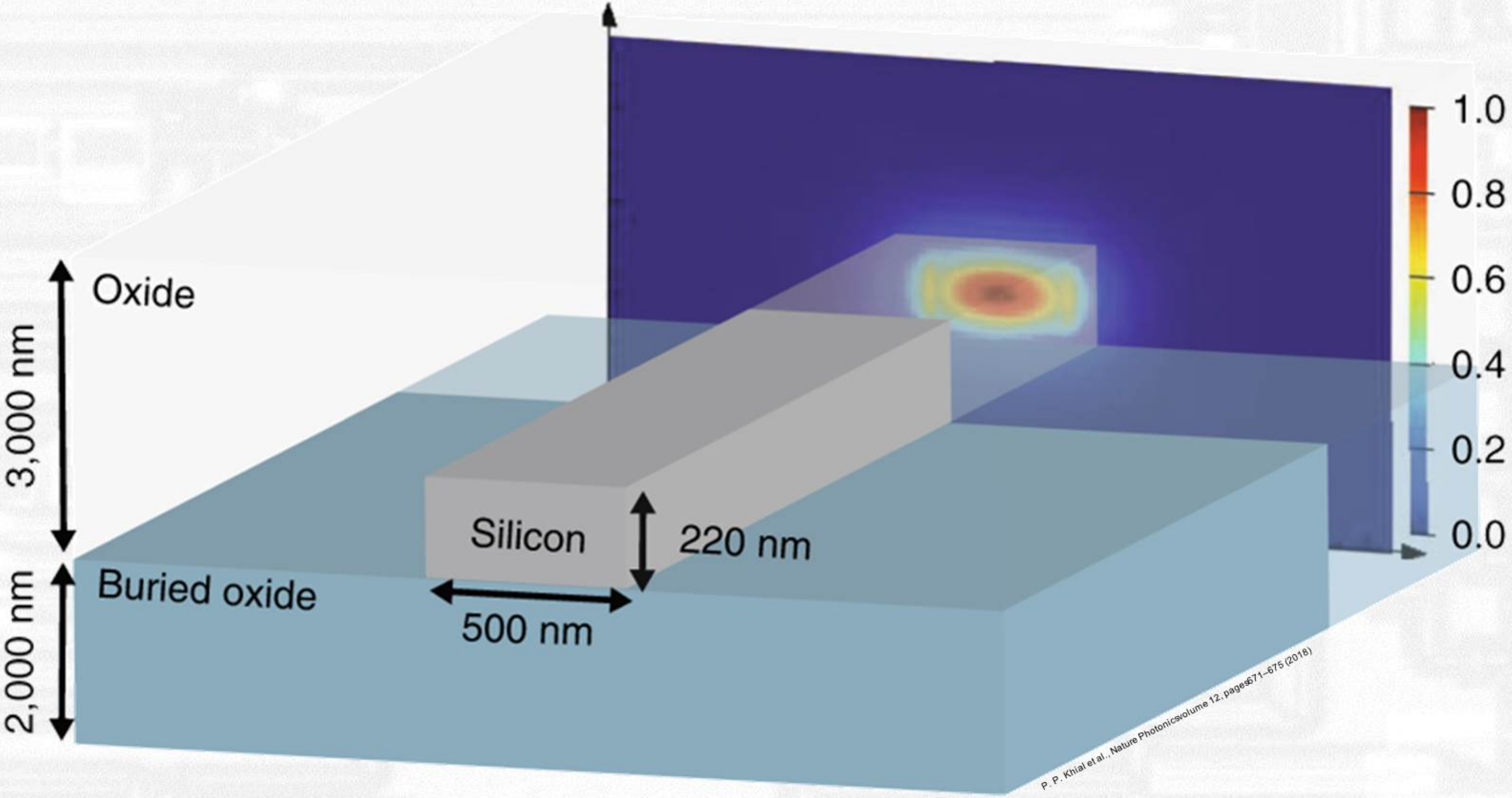


Silicon-on-Insulator: Waveguides

Film waveguide	Ridge waveguide/ Strip waveguide	Rib waveguide/ Ridge waveguide	Strip waveguide w. upper cladding	Rib waveguide w. upper cladding



Silicon-on-Insulator: Waveguides



Silicon photonic components

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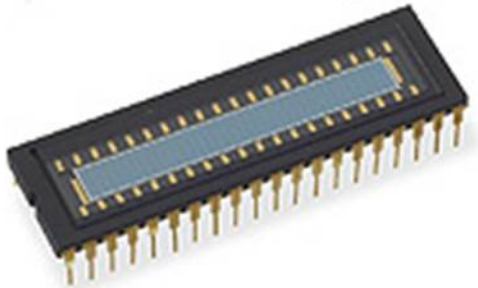
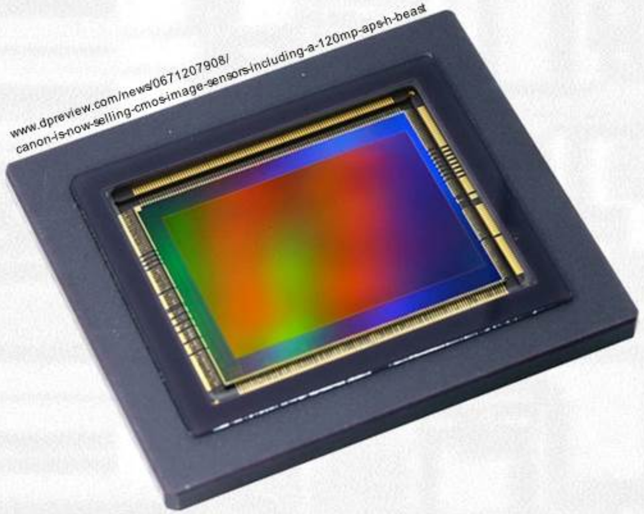
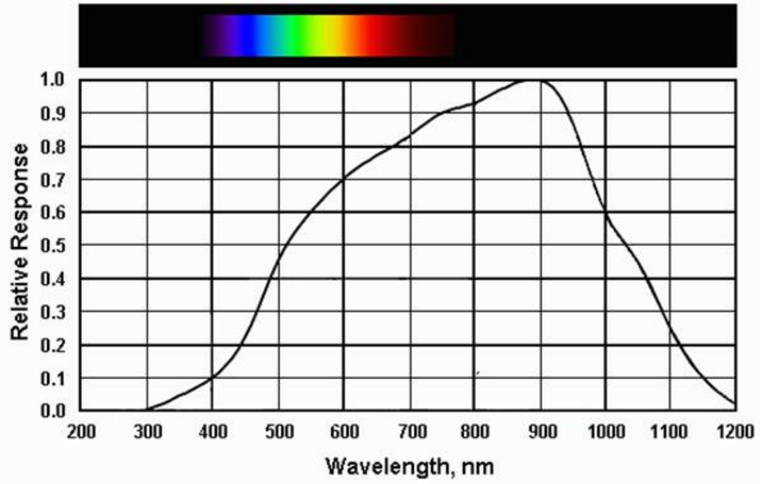
Silicon Photonics studies the generation, transmission, modulation, processing, and detection of light using silicon as the optical medium.

- *Generation: Lasers*
  - *indirect semiconductor, use nanostructures to circumvent ⇒ inferior efficiency or optical pumping with another laser ⇒ Raman laser (cheating ☺)*
- *Transmission: waveguides (see slides before)*
- *Processing: e.g. wavelength (de-)multiplexing → later*
- *Modulation: → later*
- *Detection: pn- or pin-photodiodes*

Silicon photodiodes







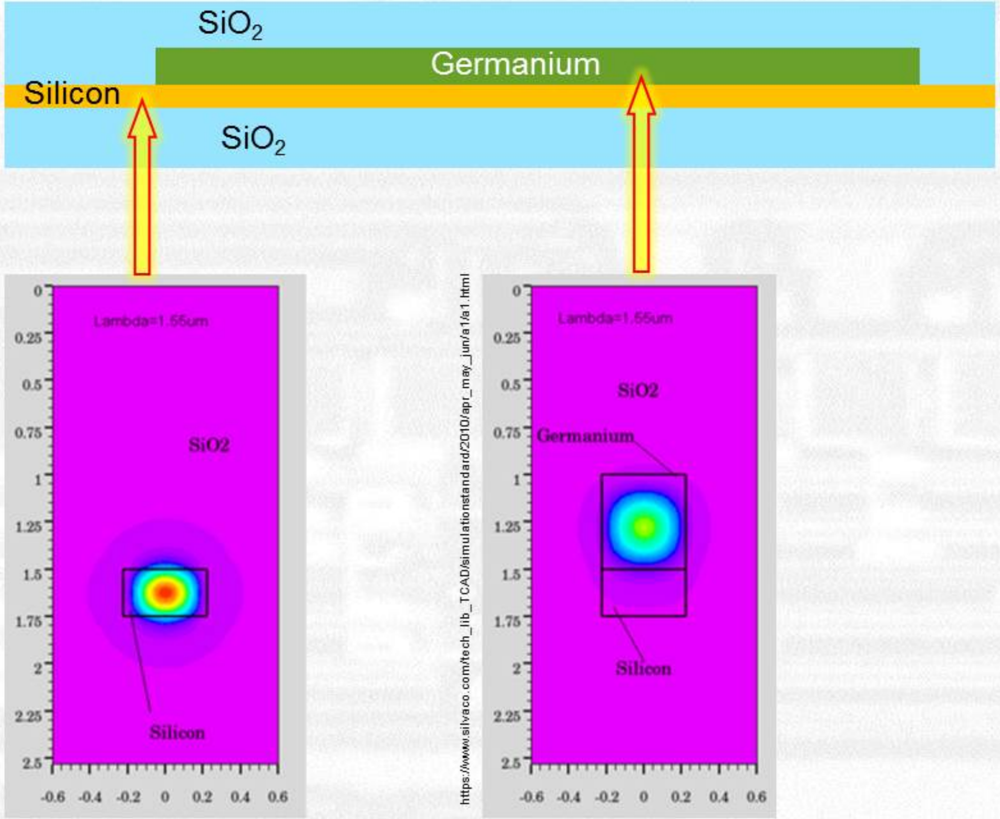
Typical Silicon Photodiode Spectral Response

courses.engr.illinois.edu/ece445/wiki/?n=Topics.LaserDiodeAndPhotodiodeIntroduction

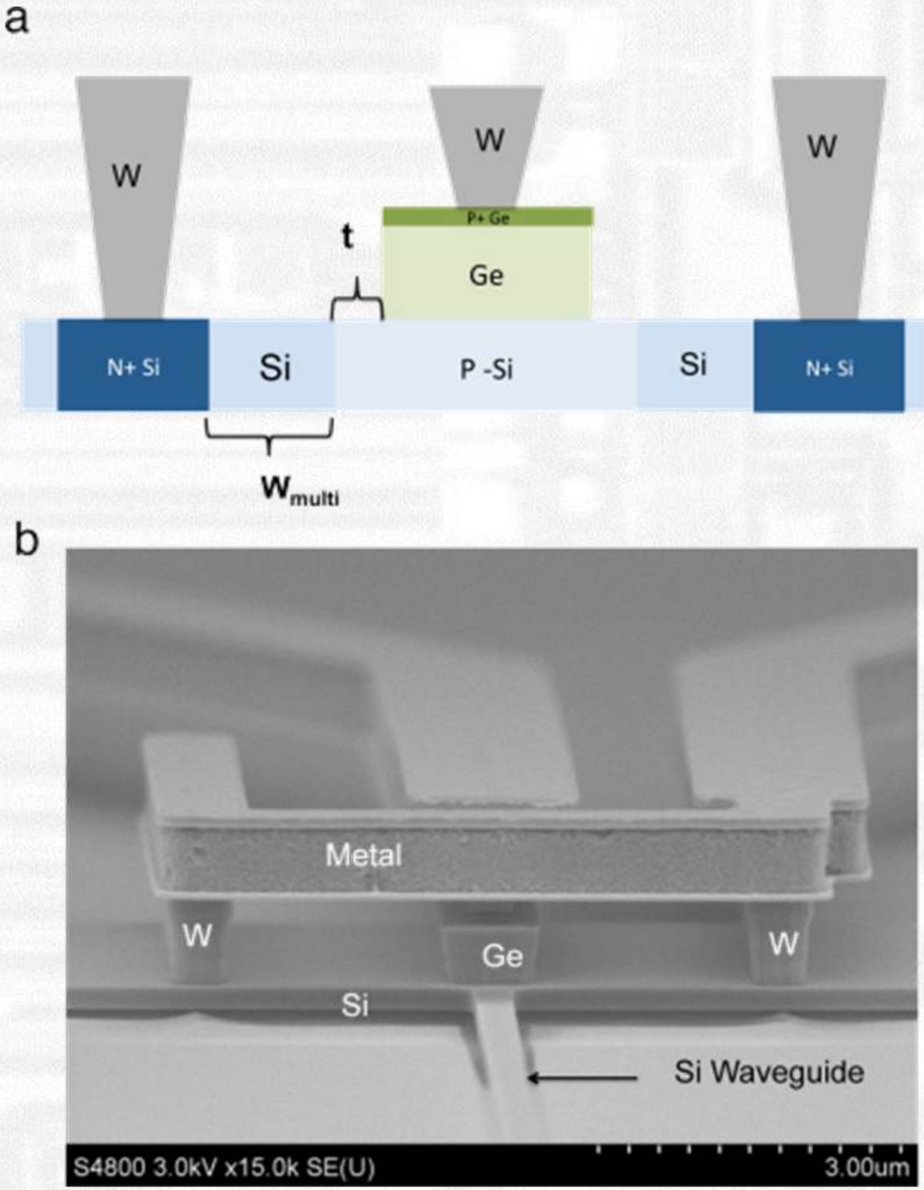
- *High absorption at low wavelengths: photodiodes*
- *Low absorption at high wavelengths: transmission and integrated optics*
- *Not both*
- *Loophole: Ge photodiodes for PICs*

Integrated photodiodes

Example: Evanescent-coupled waveguide photodiode



https://www.silvaco.com/tech_lib_TCAD/simulationstandard/2010/apr_may_jun/a1/a1.html

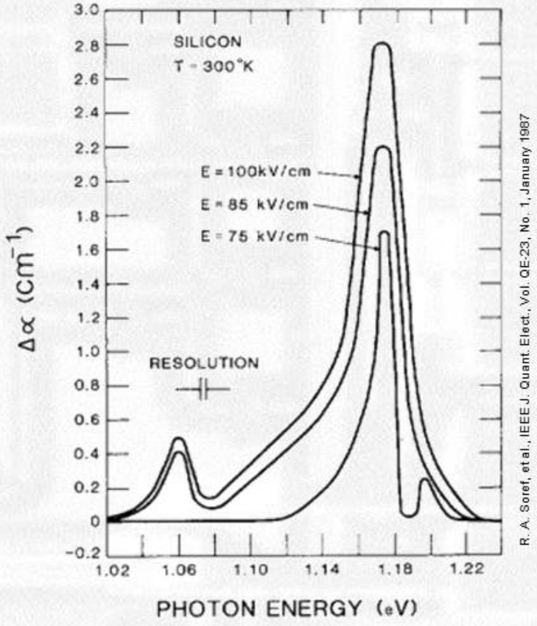


N. J. D. Martinez et al., Optics Express, Vol. 24, No. 17, pp. 19072-19081 (2016), https://doi.org/10.1364/OE.24.019072

Silicon photonic modulators

Modulate light:

- *Amplitude*
  - *Change absorption through applied E-field?*
  - *Si is indirect semiconductor*
    ⇒ weak electroabsorption, EA modulators not feasible (and λ inconvenient)
- *Phase*
  - *Change refractive index through applied E-field?*
  - *Phase modulators!*



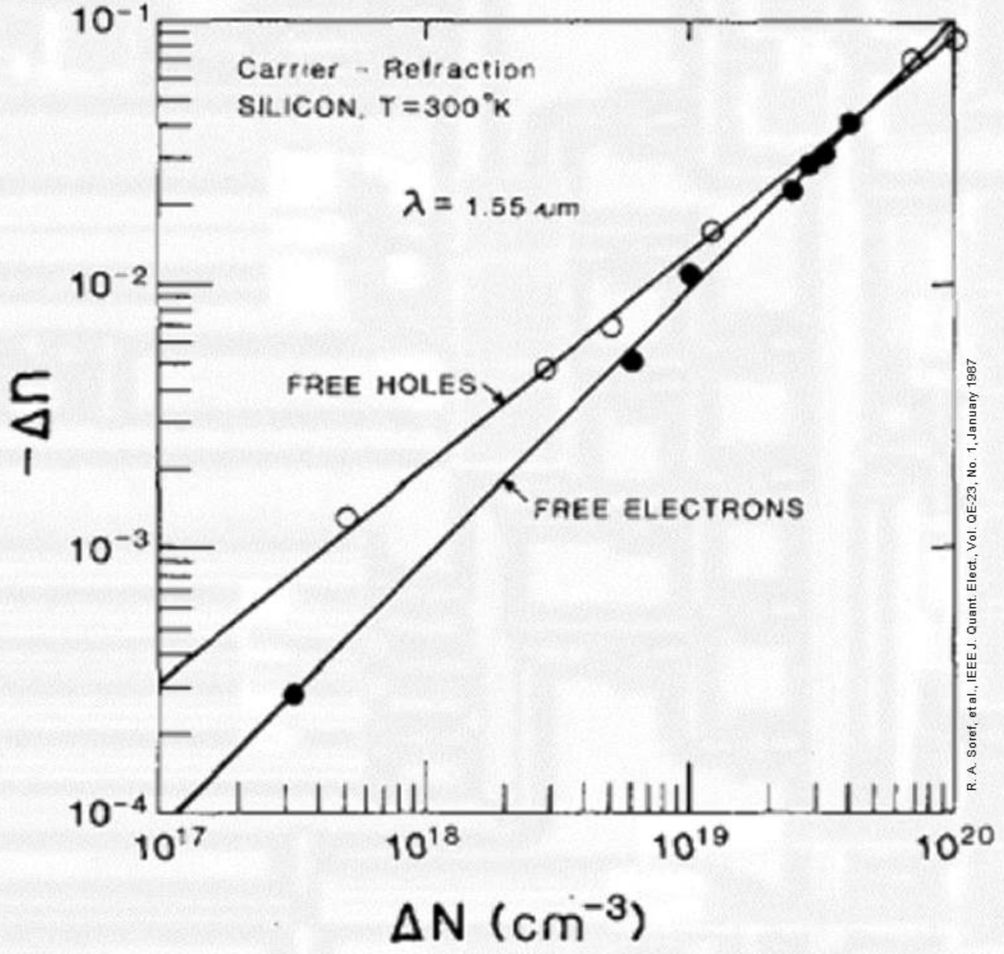
Silicon photonic modulators

Phase modulators

- *Si shows (essentially) no linear electro-optic effect (pockels effect)*
- *Charge-carrier effects*
  - *Injection of free carriers in undoped or removal of free carriers in doped Si*

$$\Delta n = -\frac{e^2\lambda^2}{8\pi^2 c^2 \epsilon_0 n}[\Delta N_e/m^*_{ce} + \Delta N_h/m^*_{ch}]$$

  - *Formula found in 1987, but major efforts in silicon photonics only since 2004*



R. A. Soref, et al., IEEE J. Quant. Elect., Vol. QE-23, No. 1, January 1987

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Silicon photonic modulators

Phase modulator

- *How to change concentration of free carriers in a waveguide?*

Silicon photonic modulators

Phase modulator

- *How to change concentration of free carriers in a waveguide?*
- *pn-junction*

Silicon photonic modulators

Phase modulator

- *How to change concentration of free carriers in a waveguide?*
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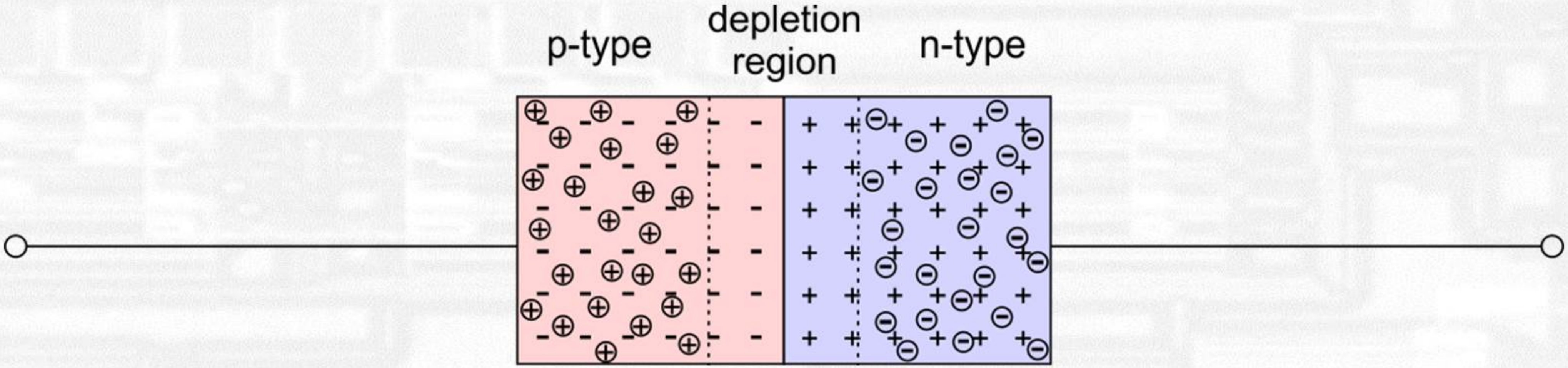
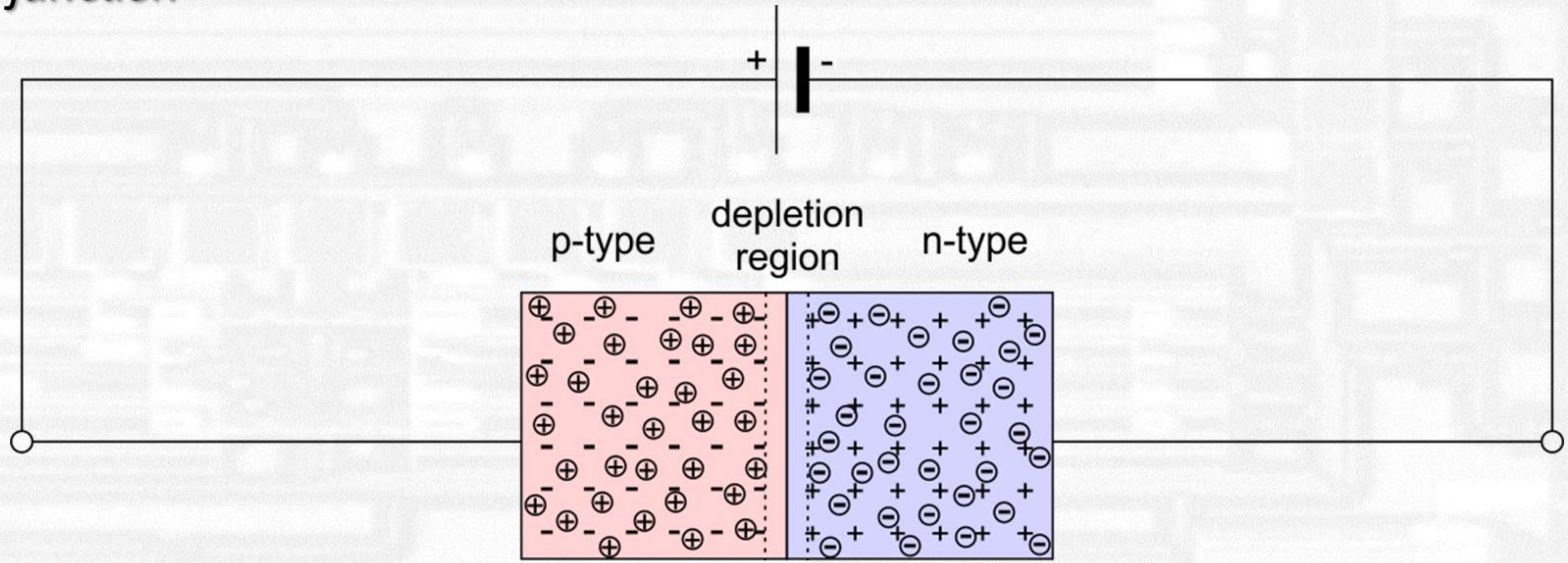


Silicon photonic modulators

Phase modulator

- How to change concentration of free carriers in a waveguide?
- pn-junction



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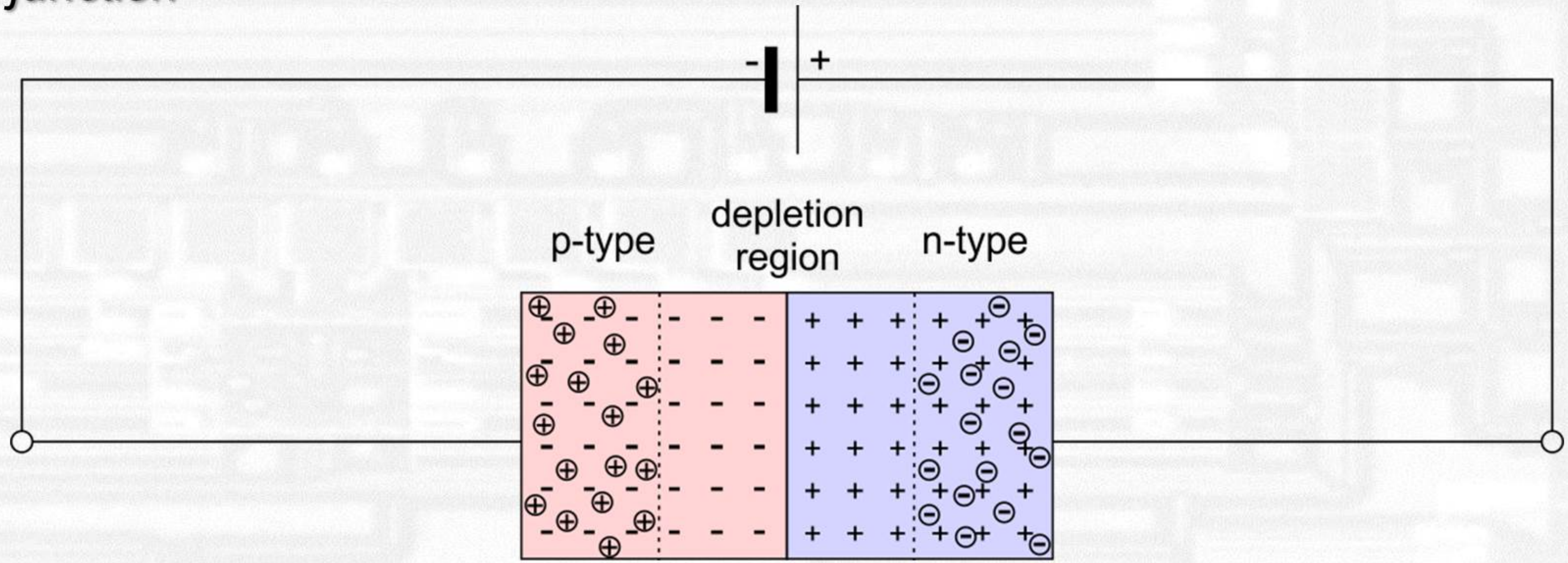
Silicon photonic modulators

Phase modulator

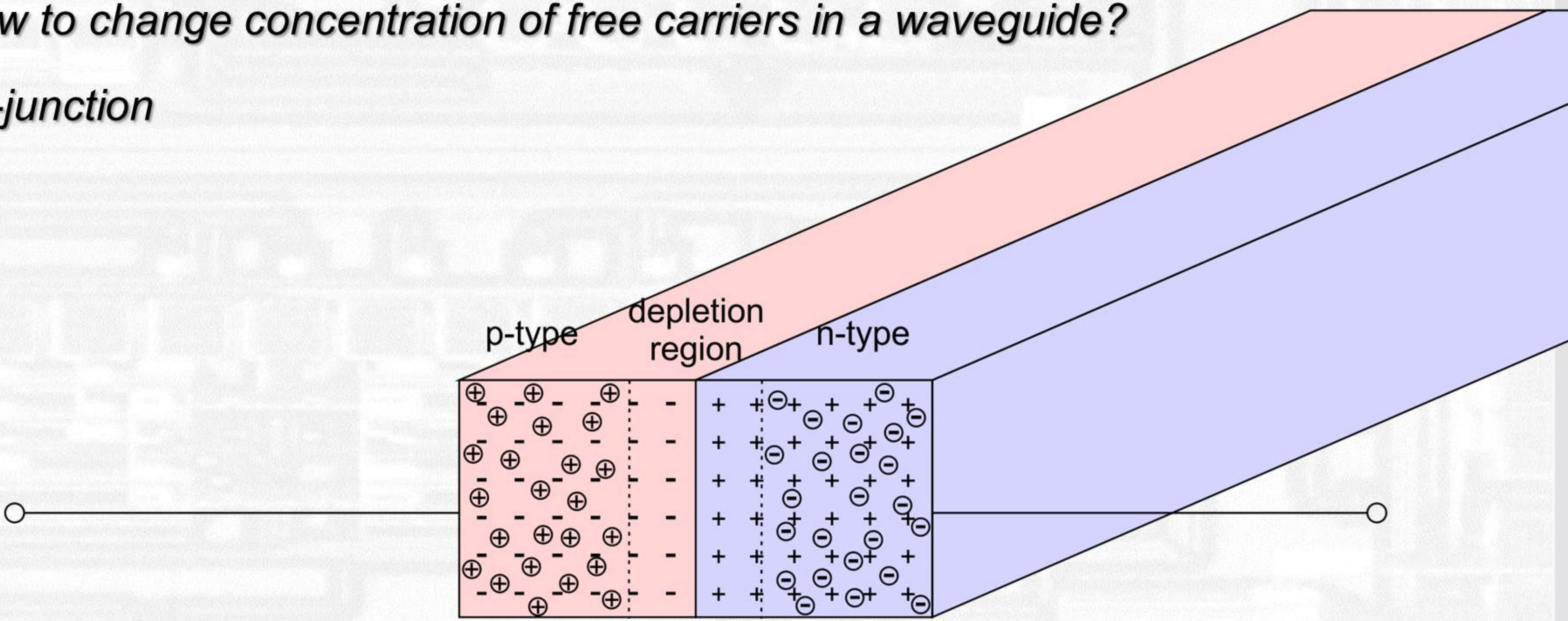
- *How to change concentration of free carriers in a waveguide?*
- *pn-junction*



Silicon photonic modulators

Phase modulator

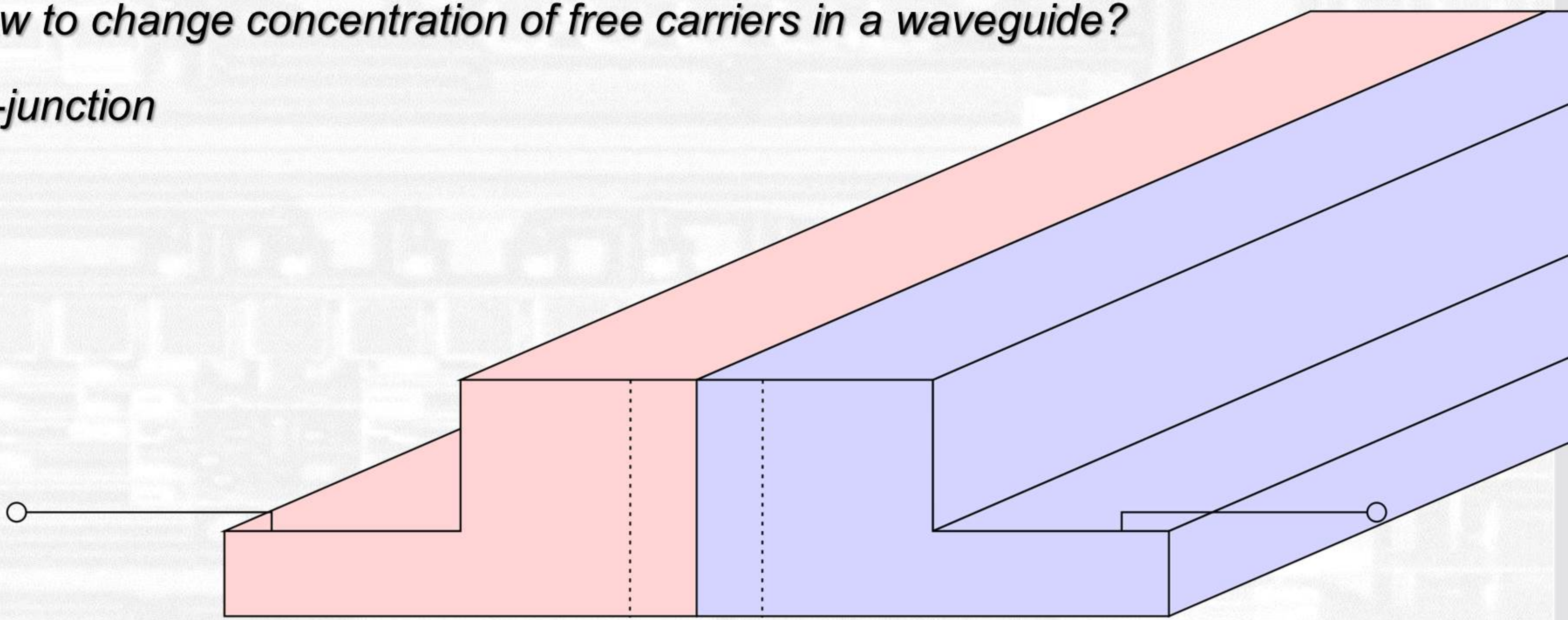
- *How to change concentration of free carriers in a waveguide?*
- *pn-junction*



Silicon photonic modulators

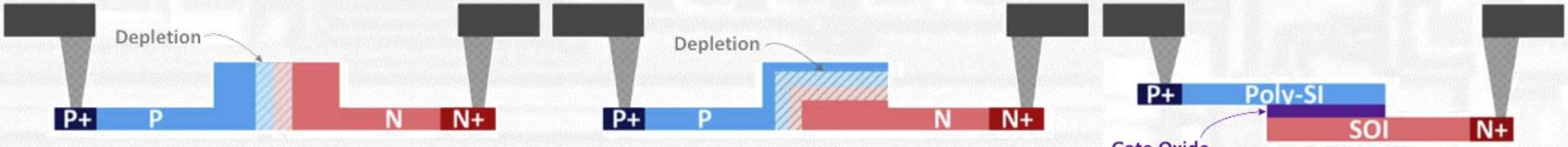
Phase modulator

- How to change concentration of free carriers in a waveguide?
- pn-junction



Silicon photonic modulators

Phase modulator: cross sections



(a) (b) (c)

Wei Shi et al., 2018 J. Opt., 20, 083002

Vertical pn-junction
- Low capacity
- Low absorption
- Easy fabrication

Horizontal pn-junction
- High capacity
- High absorption
- Complex fabrication
- Higher efficiency

Silicon-insulator-silicon capacitor (SISCAP)
- High capacity
- Very high absorption
- Complex fabrication
- High efficiency

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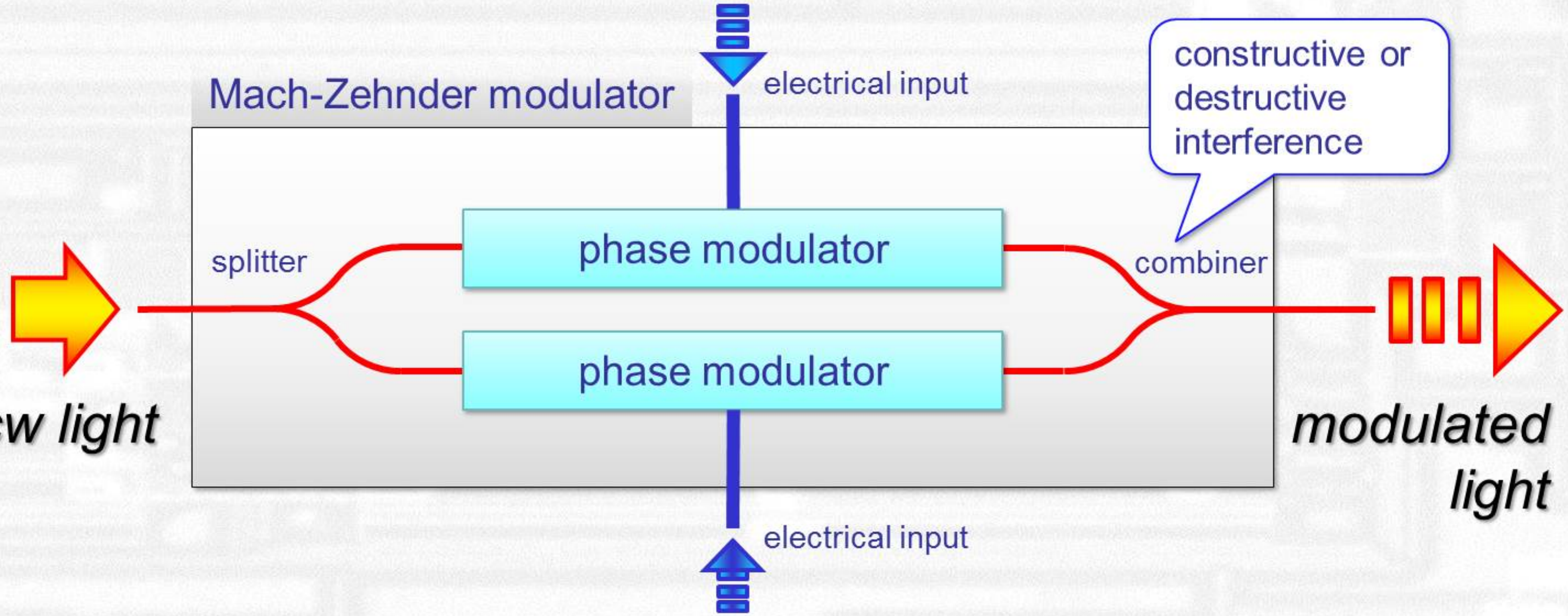
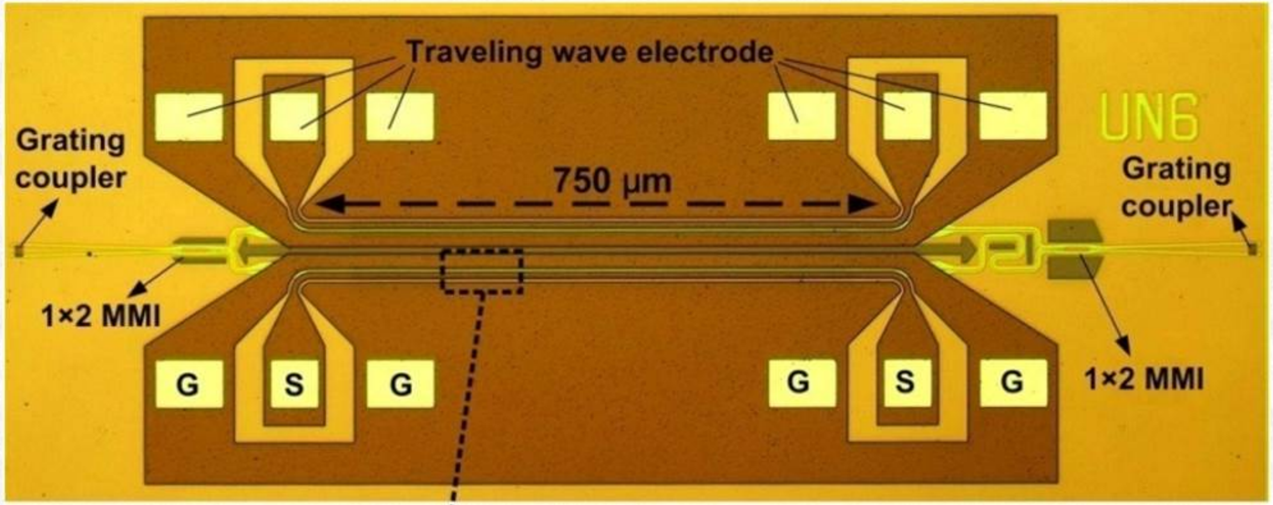
Silicon photonic modulators

Phase modulator ⇒ amplitude modulator?

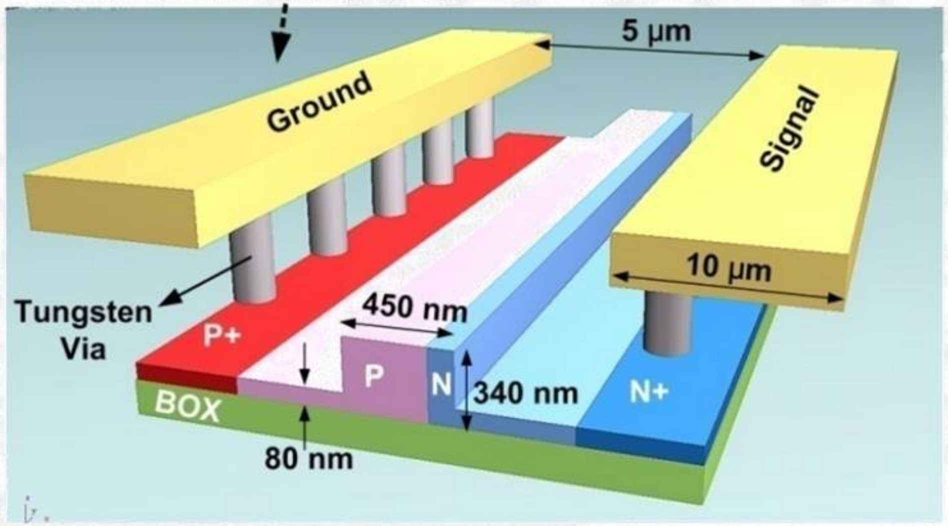
- *Mach-Zehnder interferometer*



Silicon photonic modulators



Optics Express, Vol. 21, Issue 4, pp. 4116-4125 (2013), https://doi.org/10.1364/OE.21.004116



Xi Xiao, Hao Xu, Xianyao Li, Zhiyong Li, Tao Chu, Yude Yu, and Jinzhong Yu,

High-speed, low-loss silicon Mach–Zehnder modulators with doping optimization

Optics Express, Vol. 21, Issue 4, pp. 4116-4125 (2013), https://doi.org/10.1364/OE.21.004116

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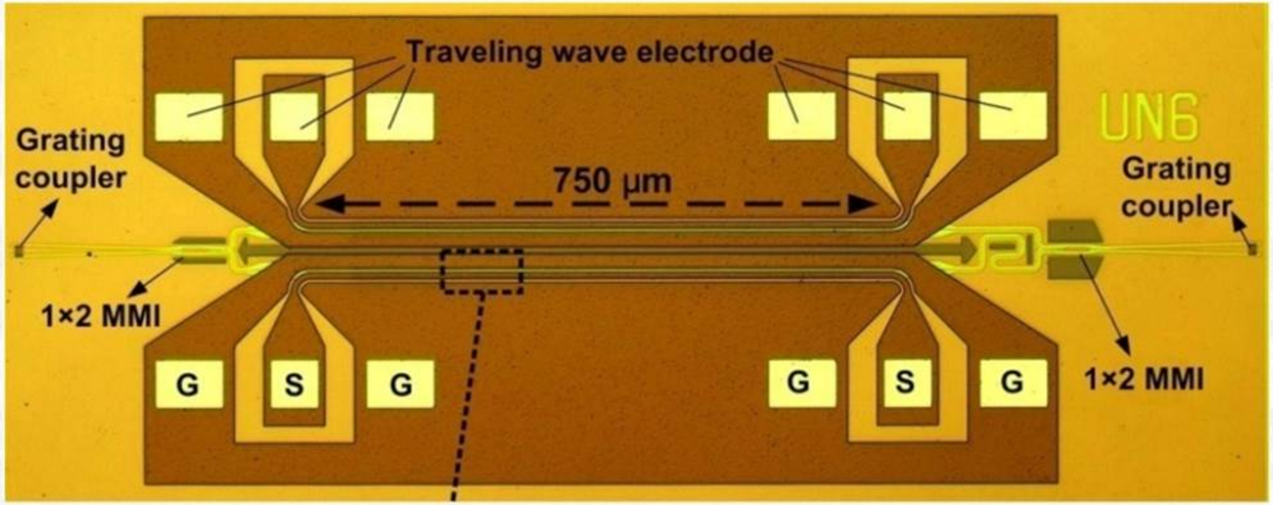
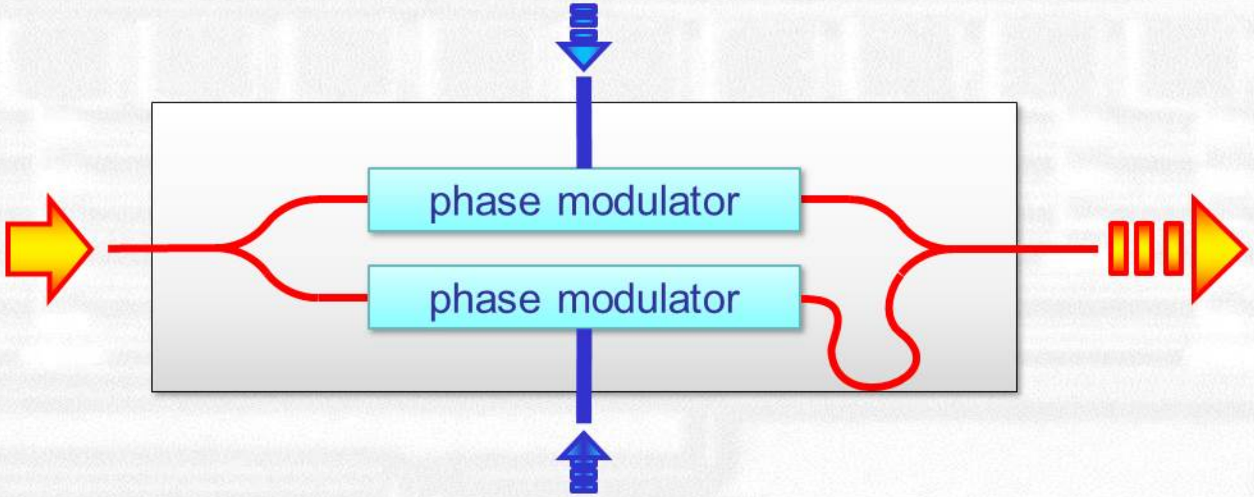
Silicon photonic modulators

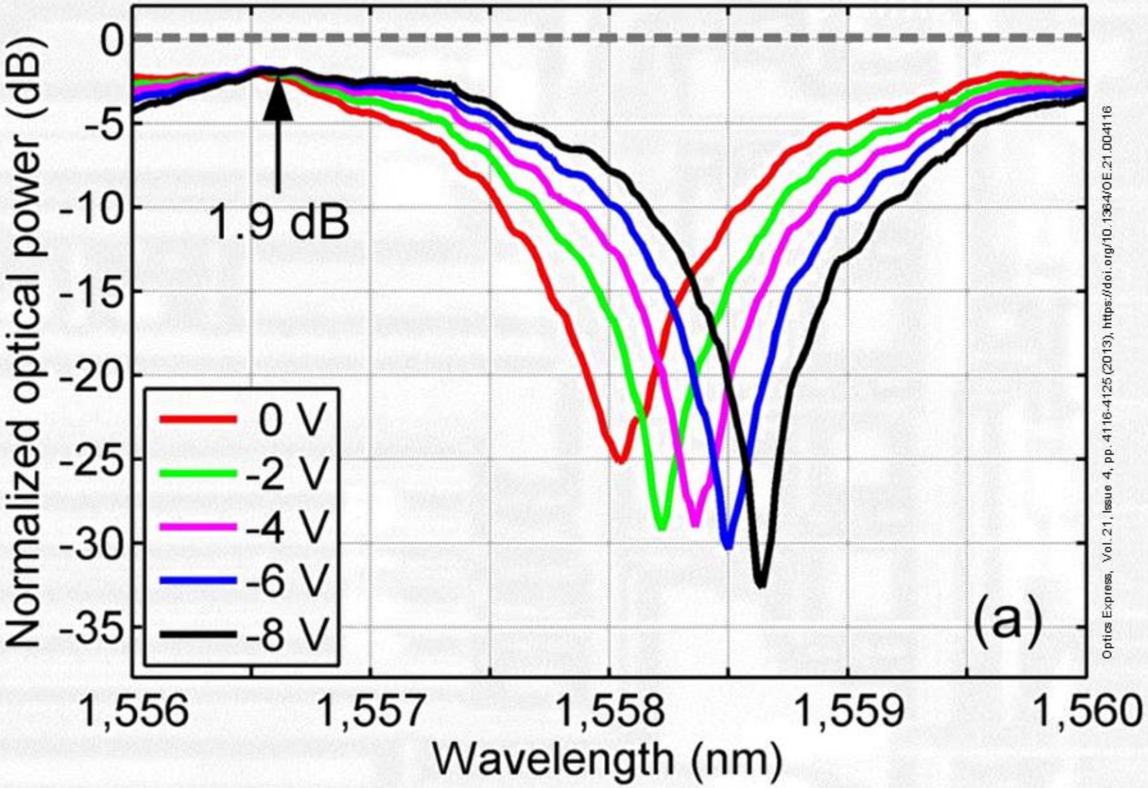


Optics Express, Vol. 21, Issue 4, pp. 4116-4125 (2013), https://doi.org/10.1364/OE.21.004116

asymmetric MZM

⇒ *easy DC characterization*





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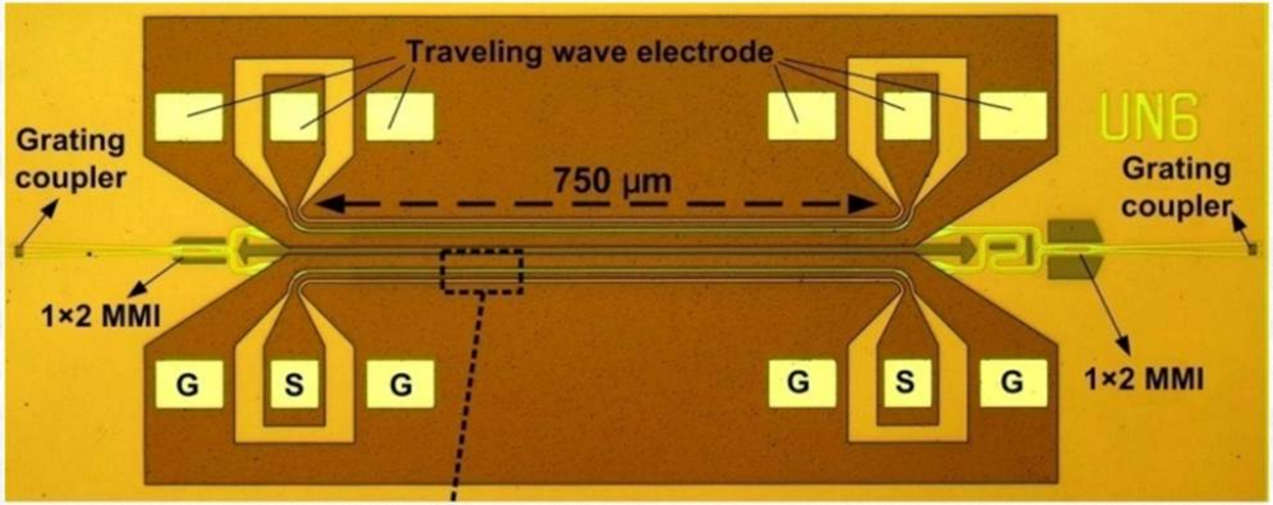
Silicon photonic modulators



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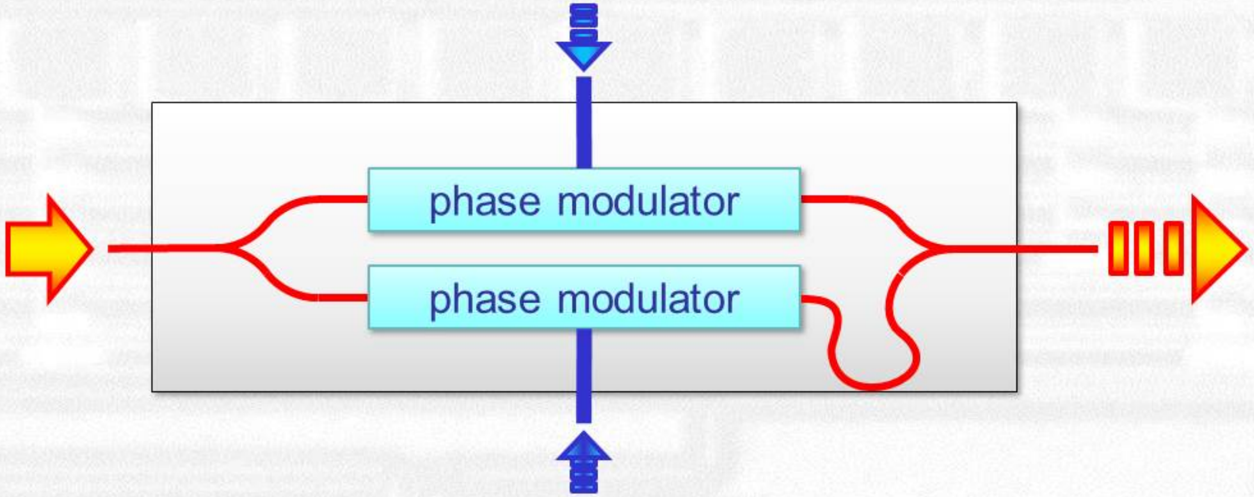
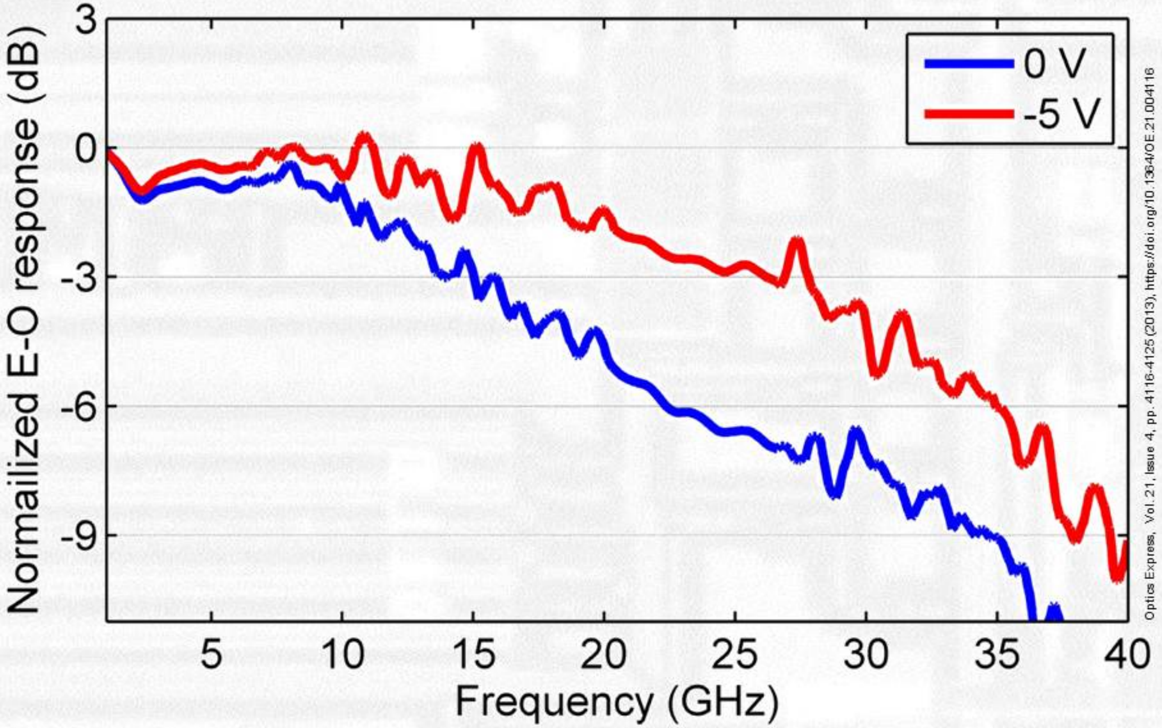


RF characterization



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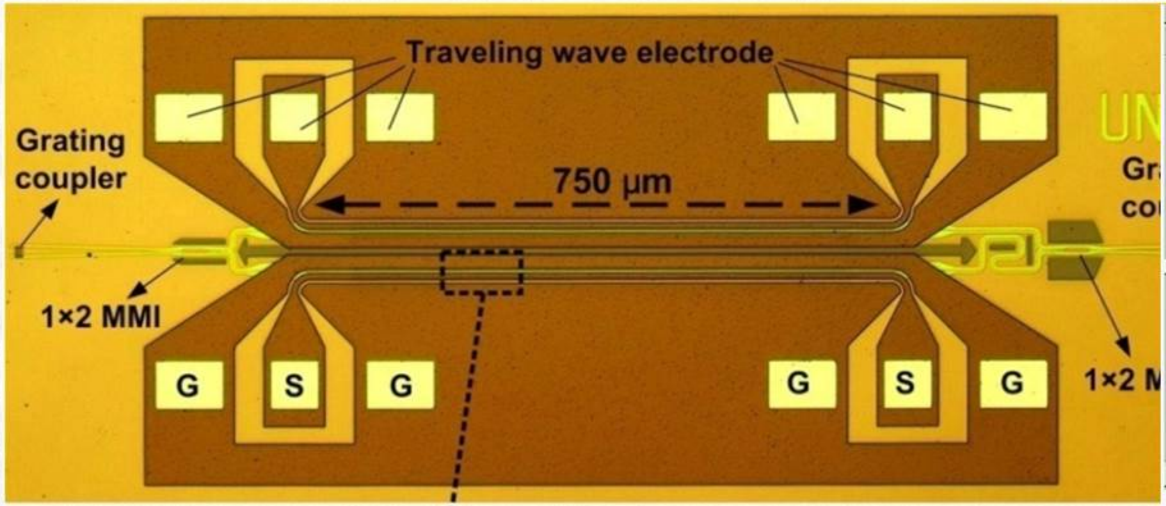
Silicon photonic modulators



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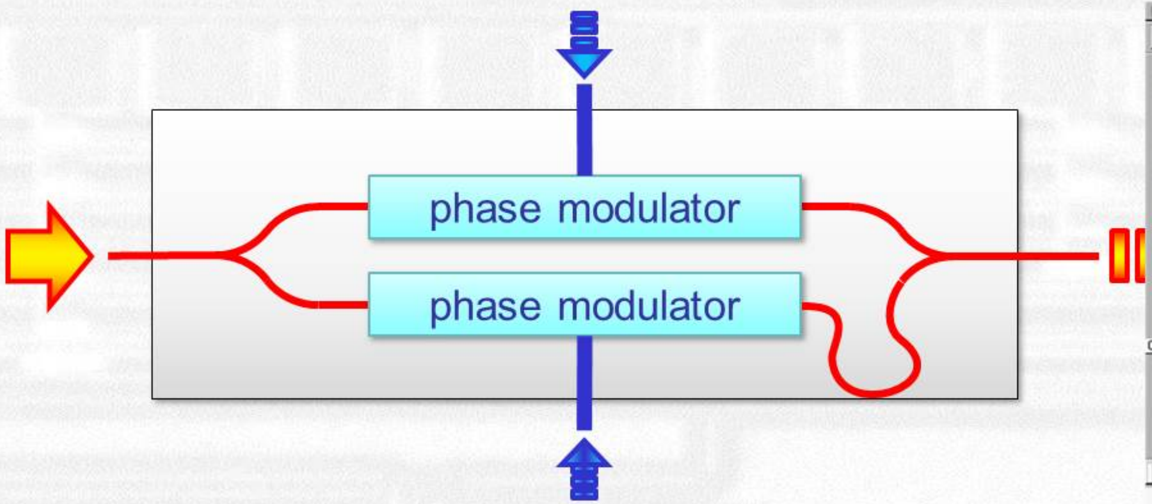

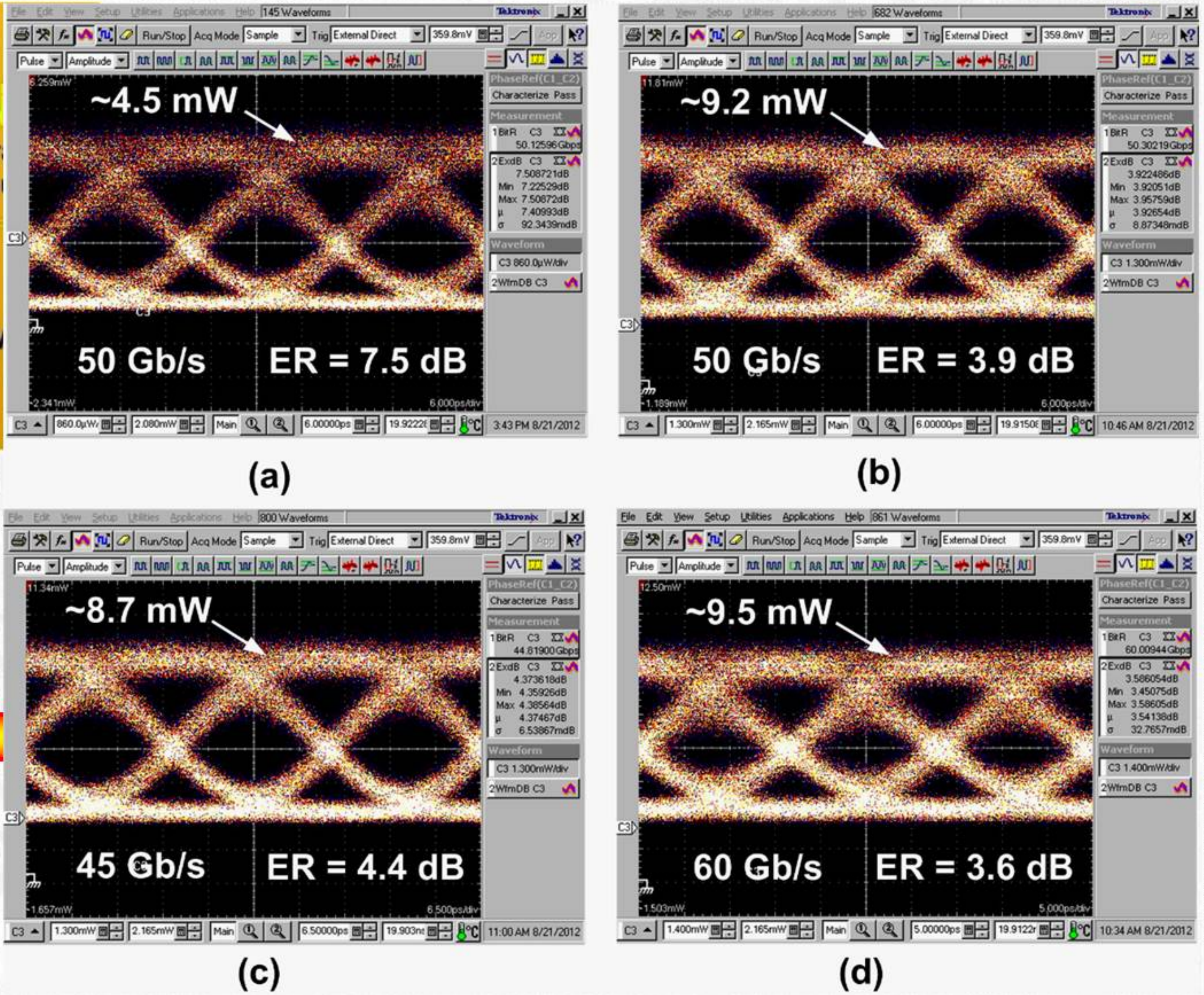

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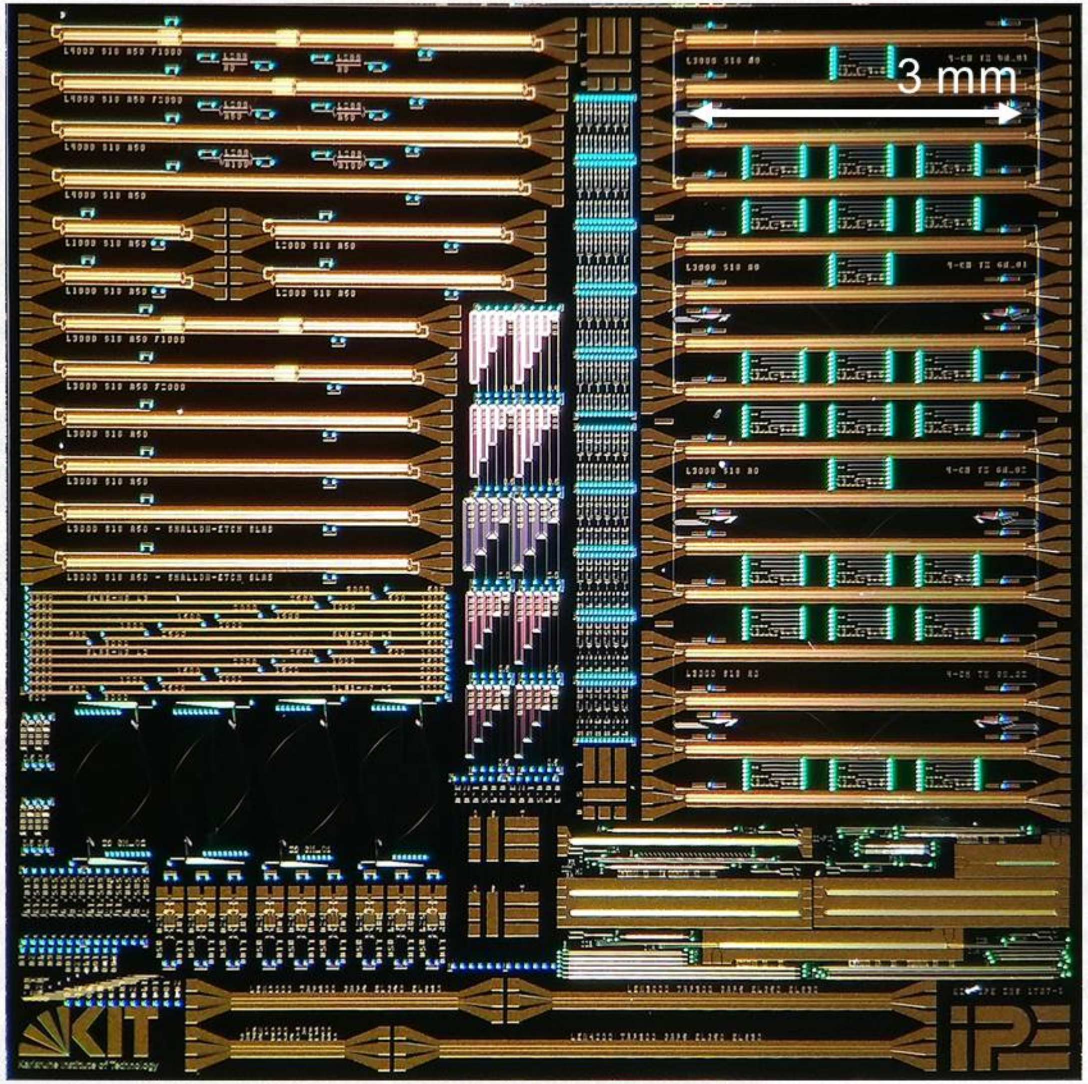
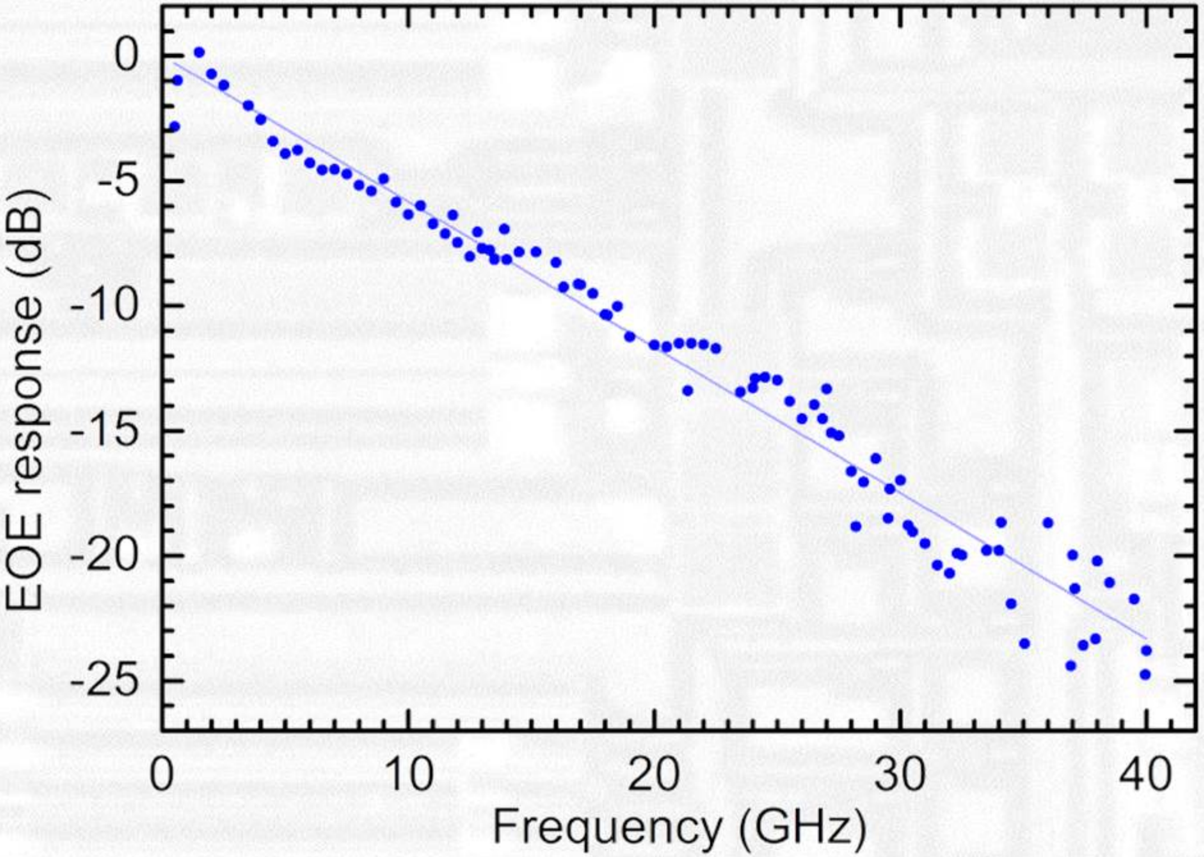
Silicon photonic modulators

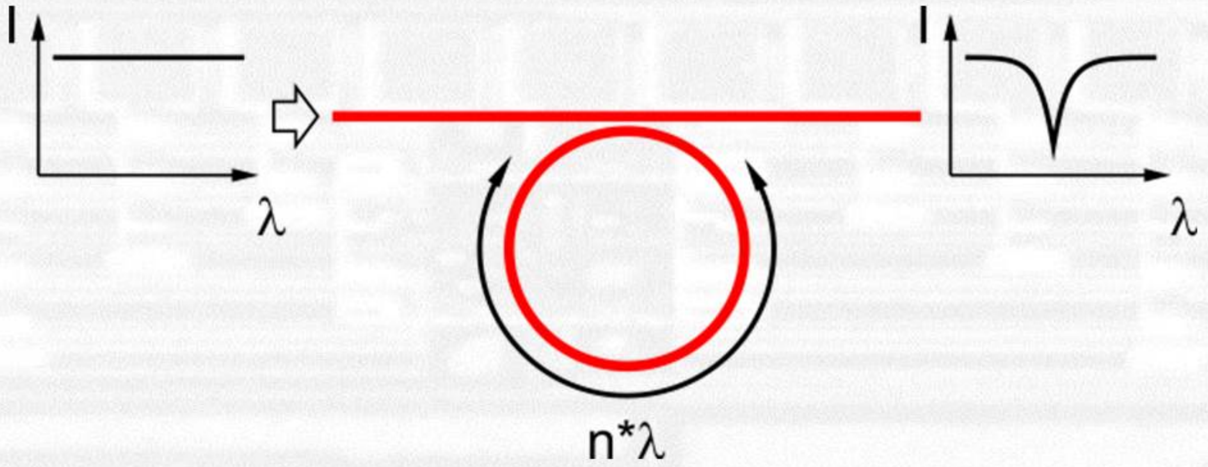


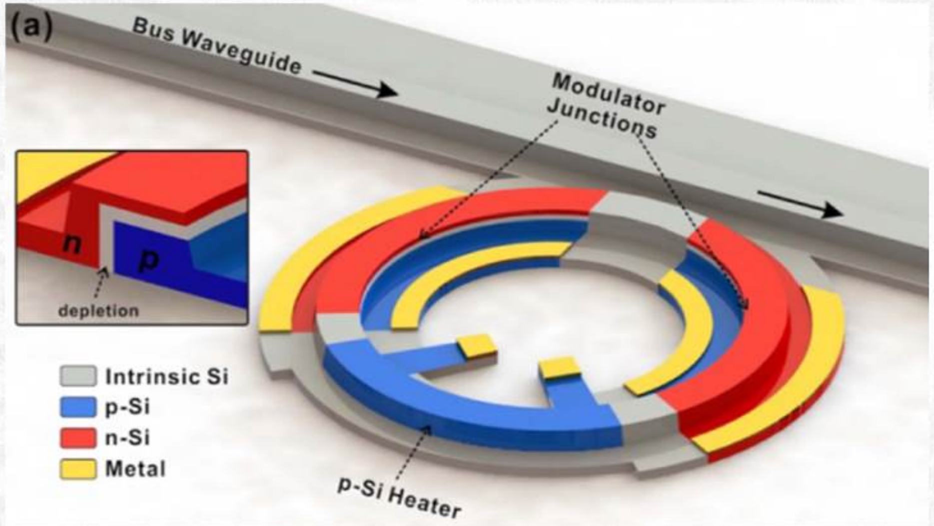


Silicon photonic modulators

Ring modulators

- *Resonant and slightly absorbing ring, coupled to a bus waveguide*
- *At the resonance wavelength, light is coupled out of the bus waveguide and damped away*





Wei Shi et al., 2018 J. Opt. 20 083002

Silicon photonic modulators

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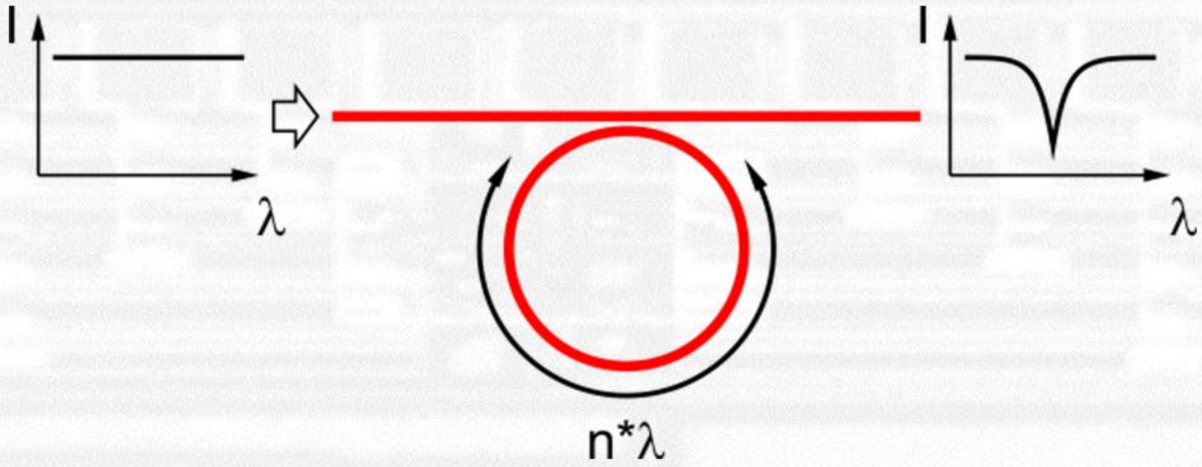

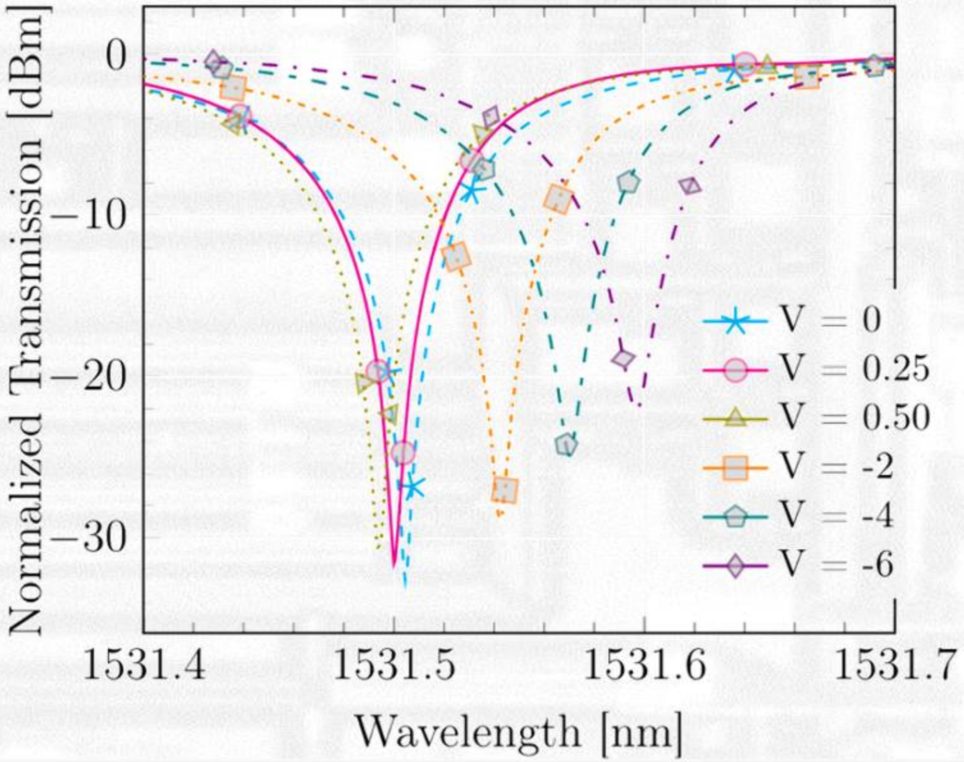

R. Dubé-Demers et al., Optica 3 (6), pp. 622-627 (2016), https://doi.org/10.1364/OPTICA.3.000622

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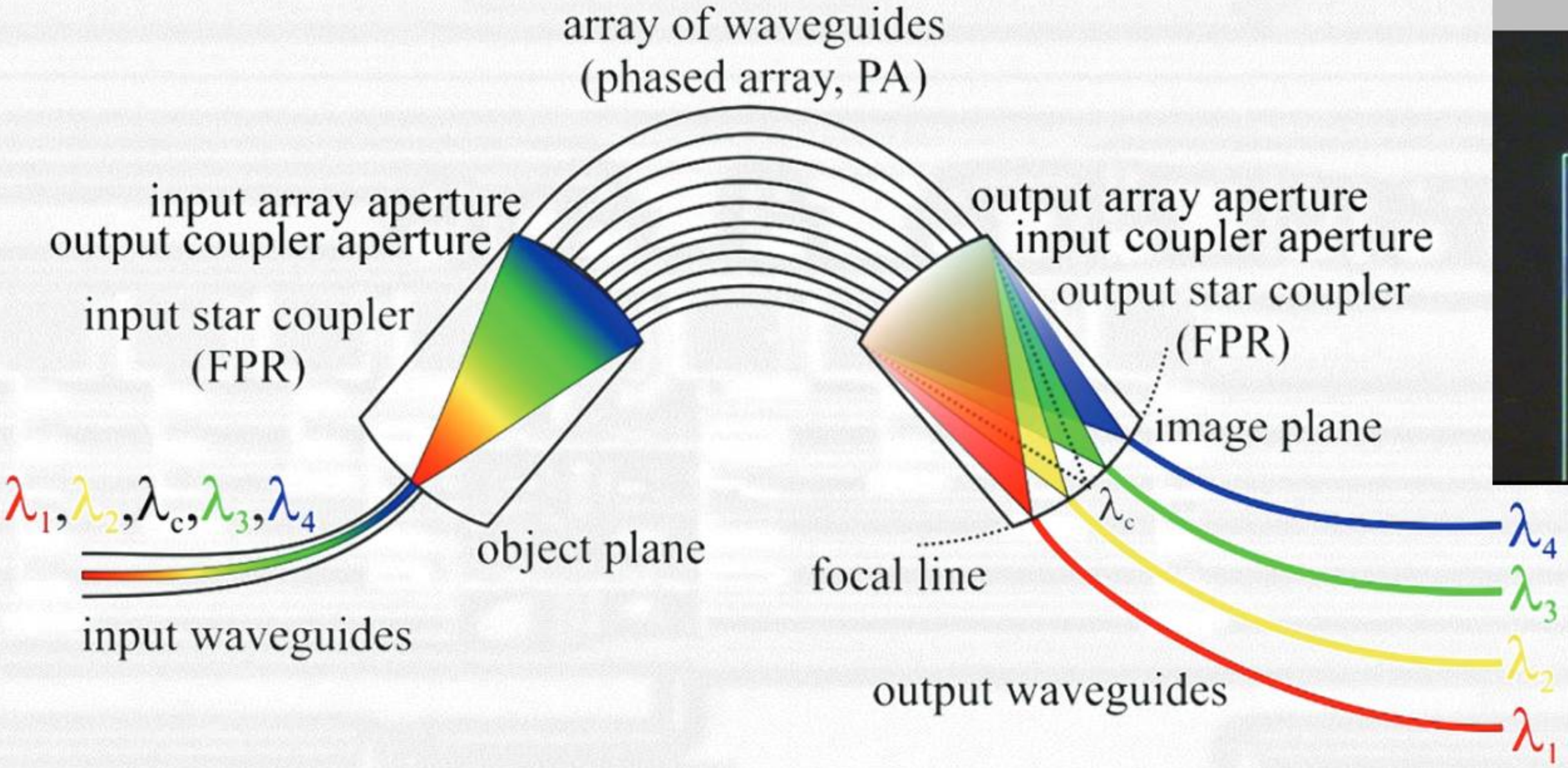
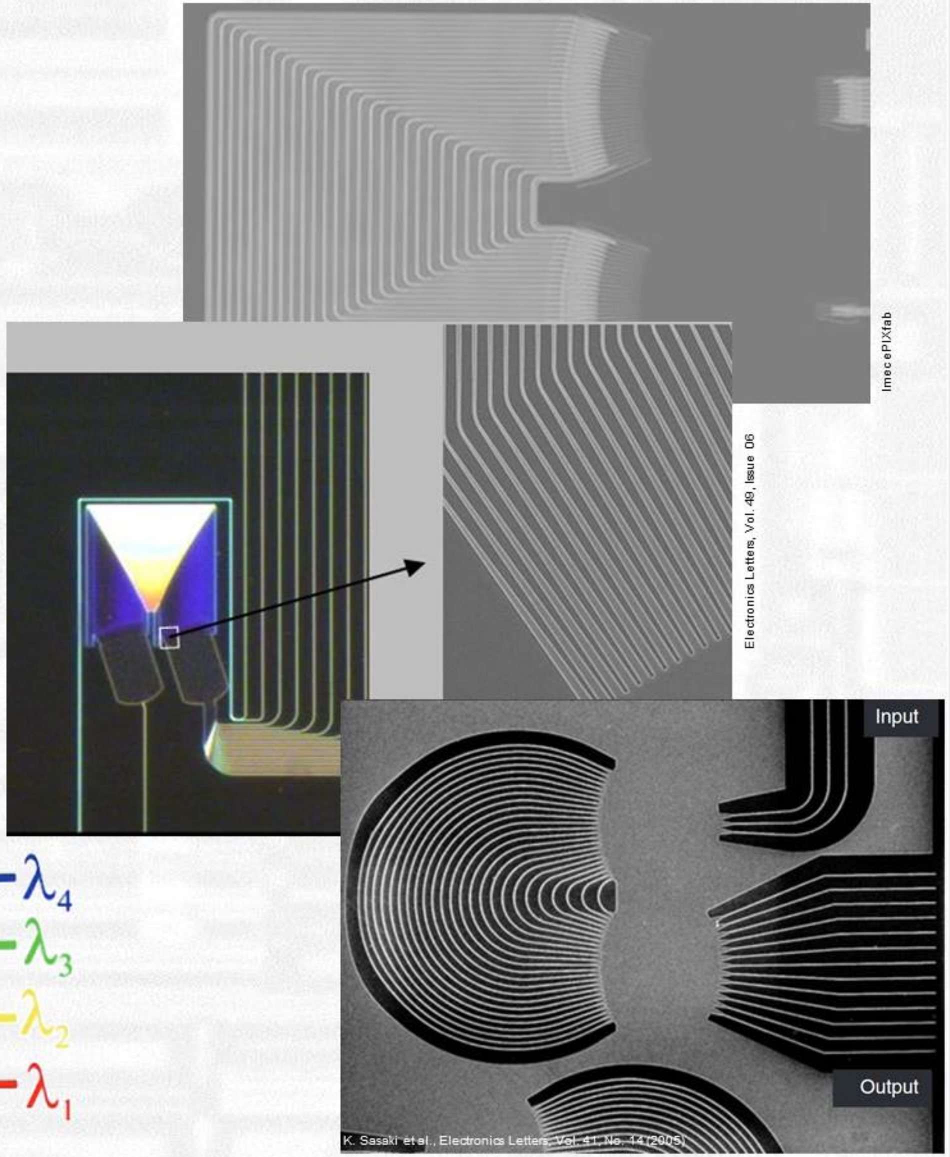
Processing of light

Wavelength multiplexers and demultiplexers

- Arrayed waveguide gratings

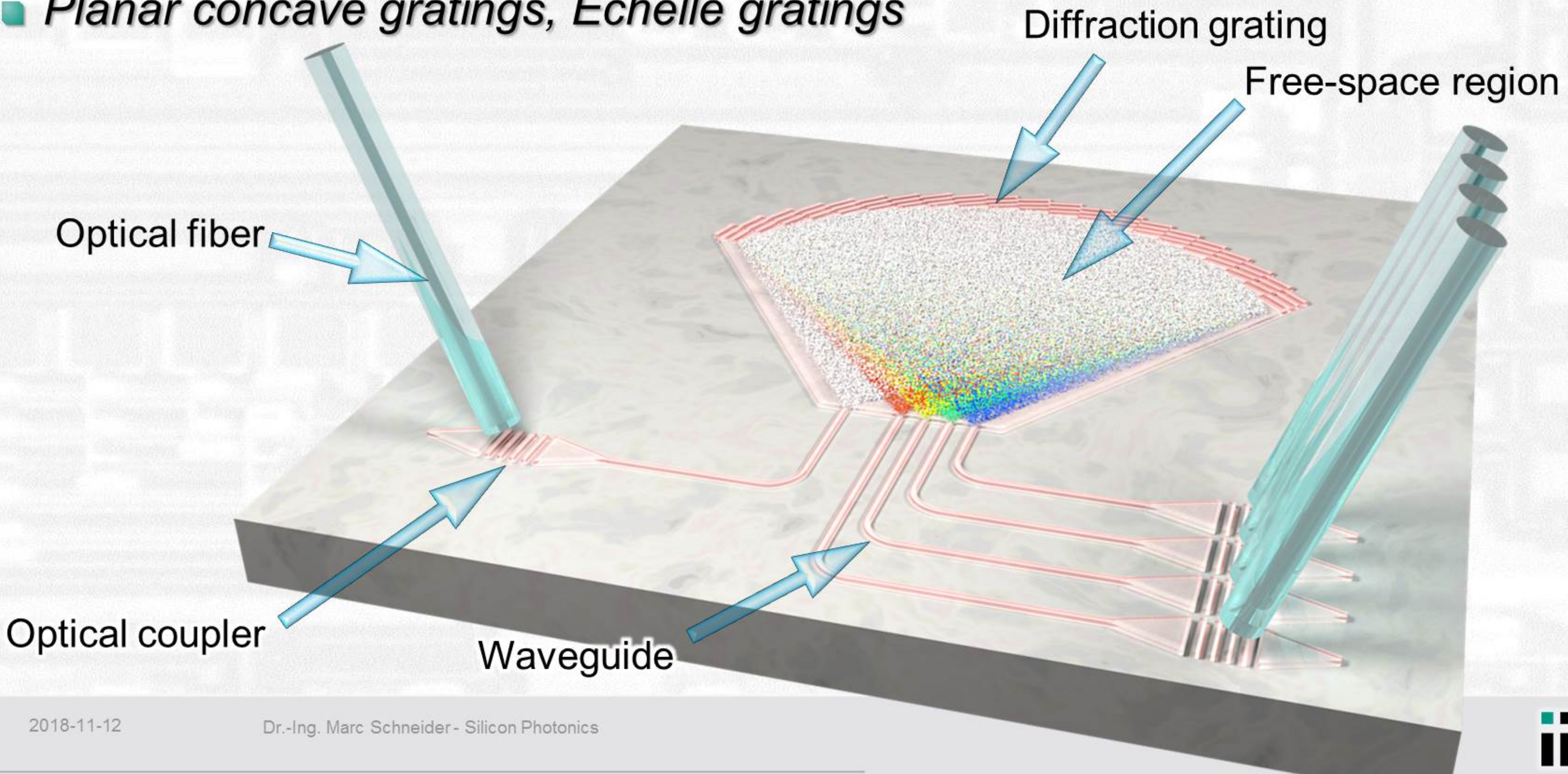




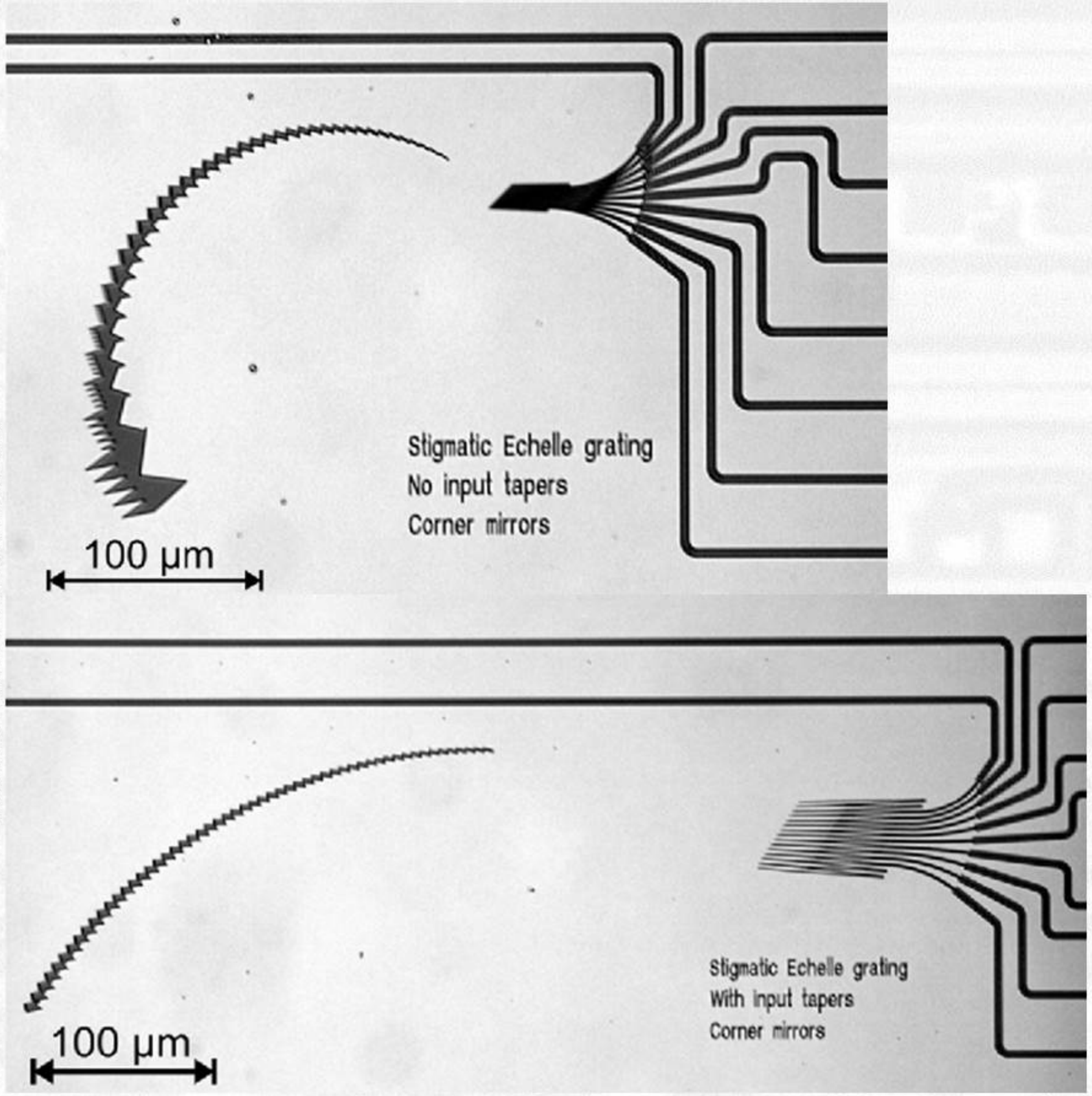
Processing of light

Wavelength multiplexers and demultiplexers

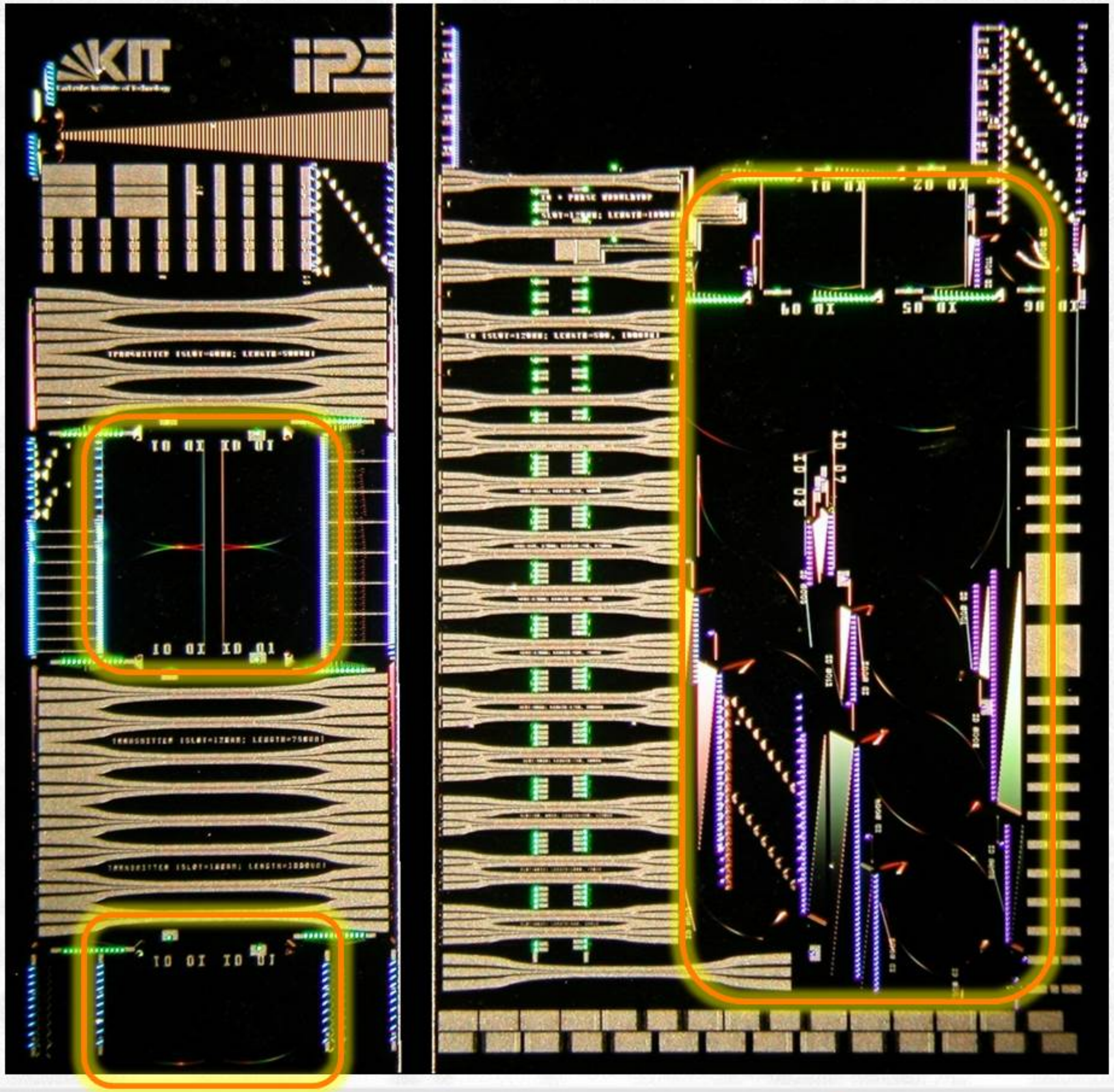
- *Planar concave gratings, Échelle gratings*



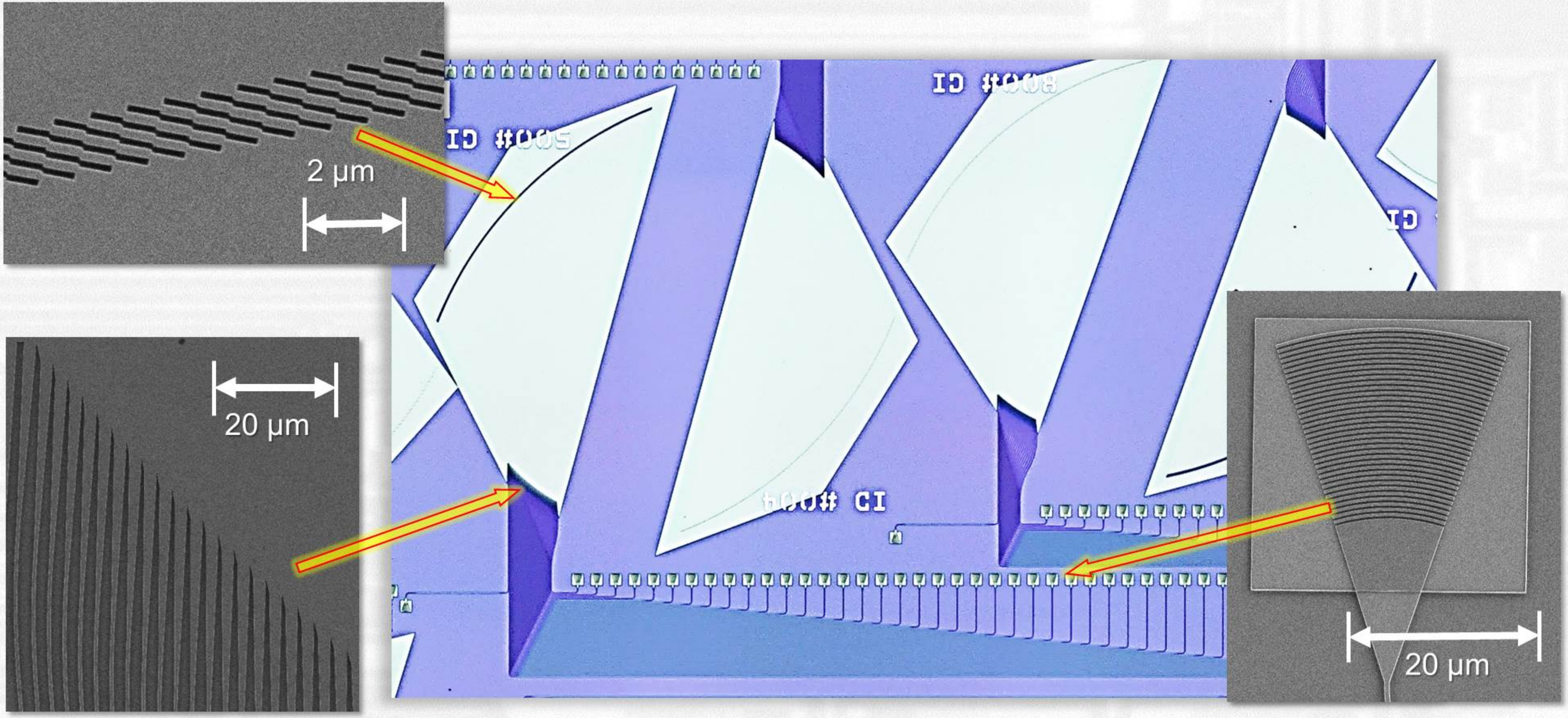
(De-)Multiplexers



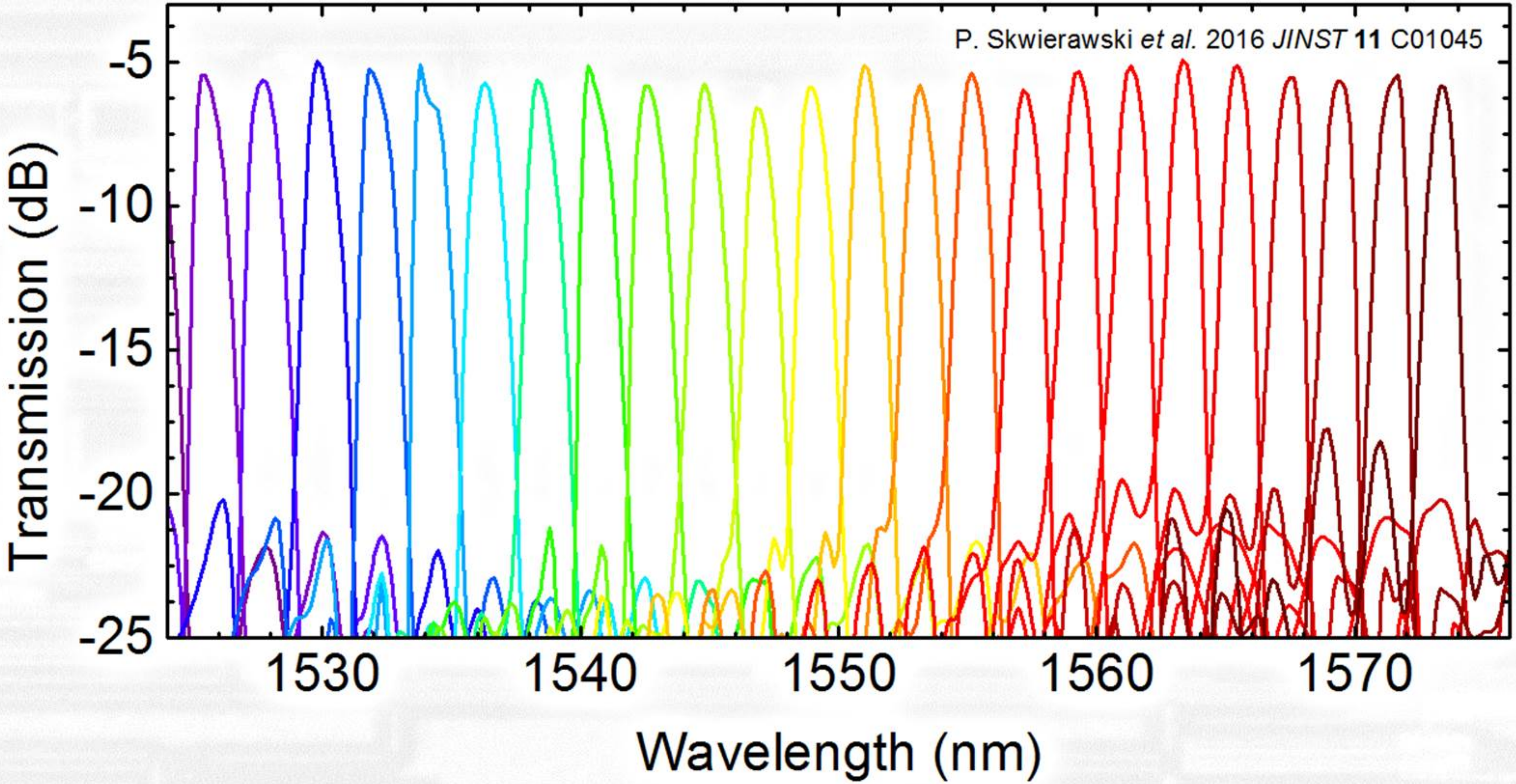
F. Horst et al., IEEE Phot. Technol. Lett. 21 (23), pp. 1743-1745 (2009)



(De-)Multiplexers



(De-)Multiplexers



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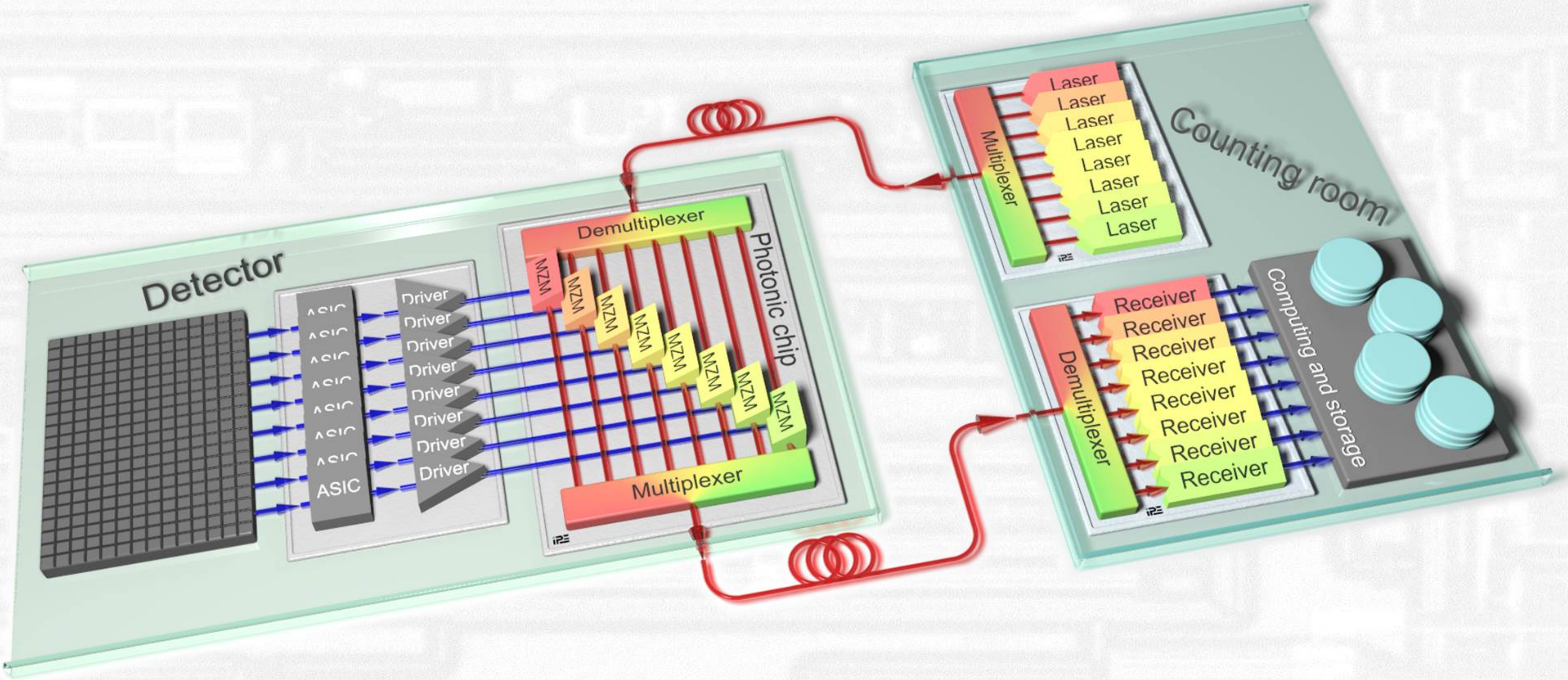
What to do with the components?

WDM-System



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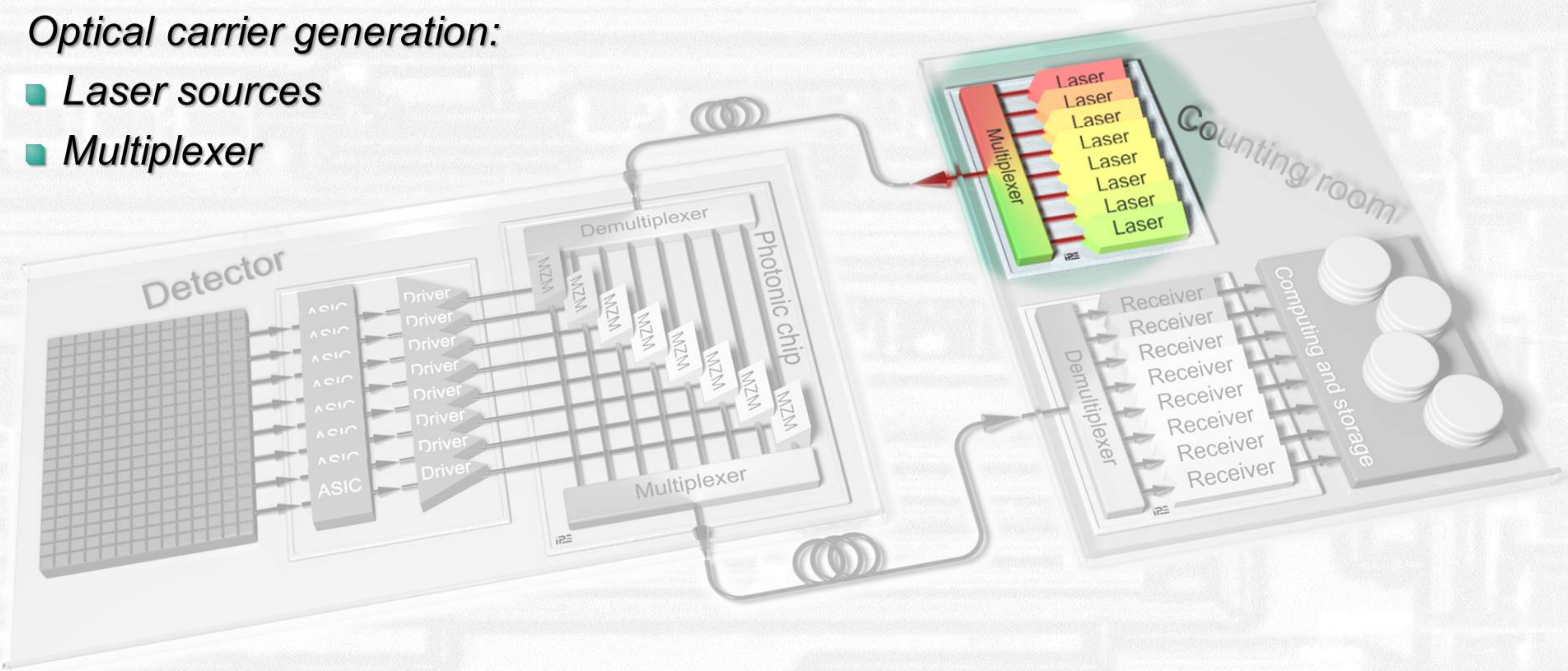
WDM-System

Optical carrier generation:

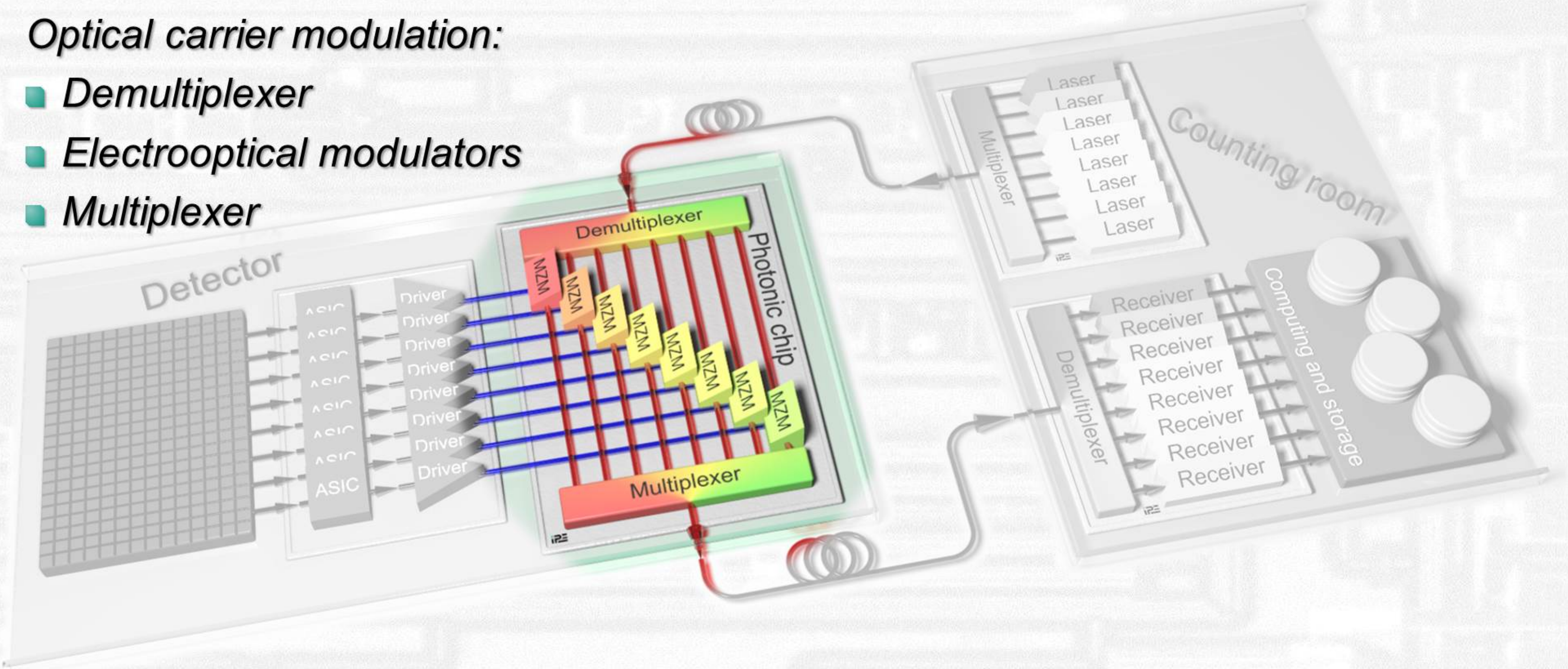
- *Laser sources*
- *Multiplexer*



WDM-System

Optical carrier modulation:

- *Demultiplexer*
- *Electrooptical modulators*
- *Multiplexer*



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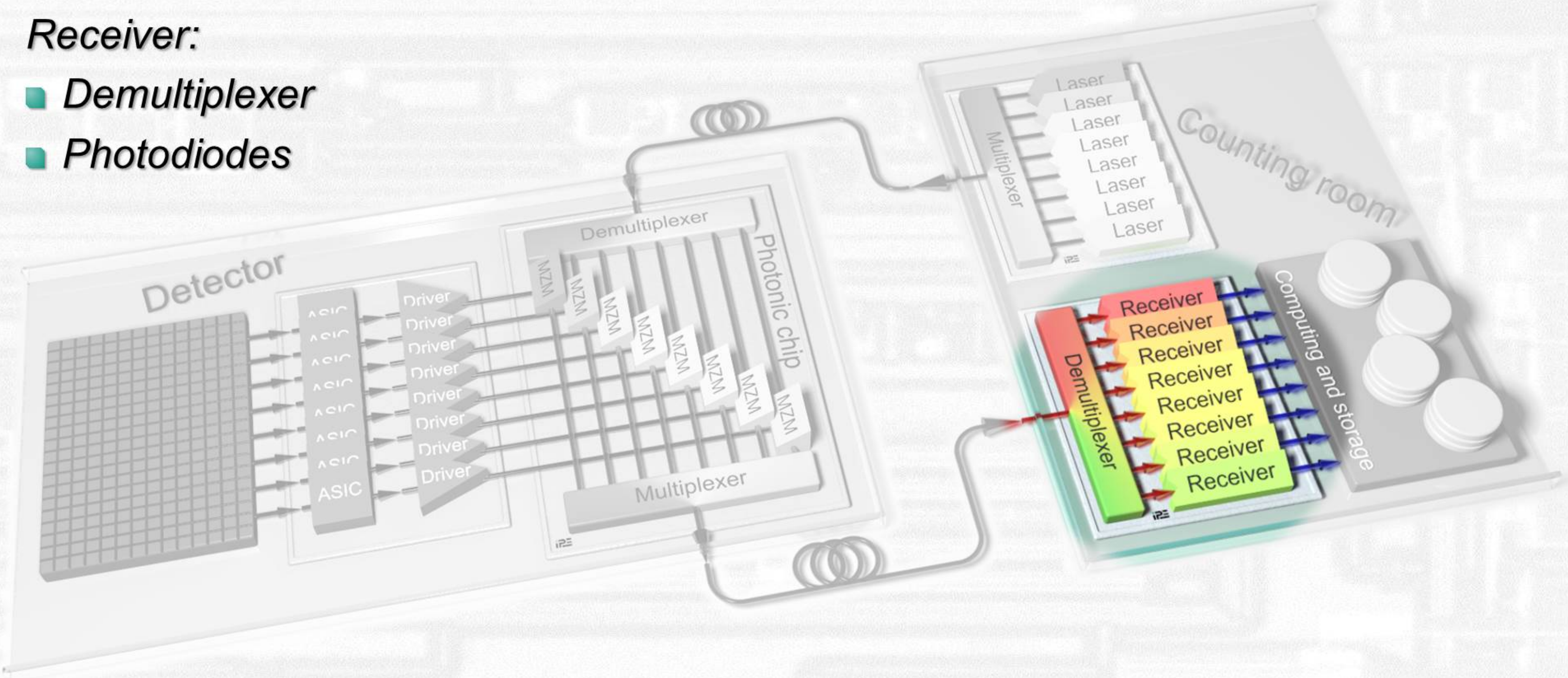
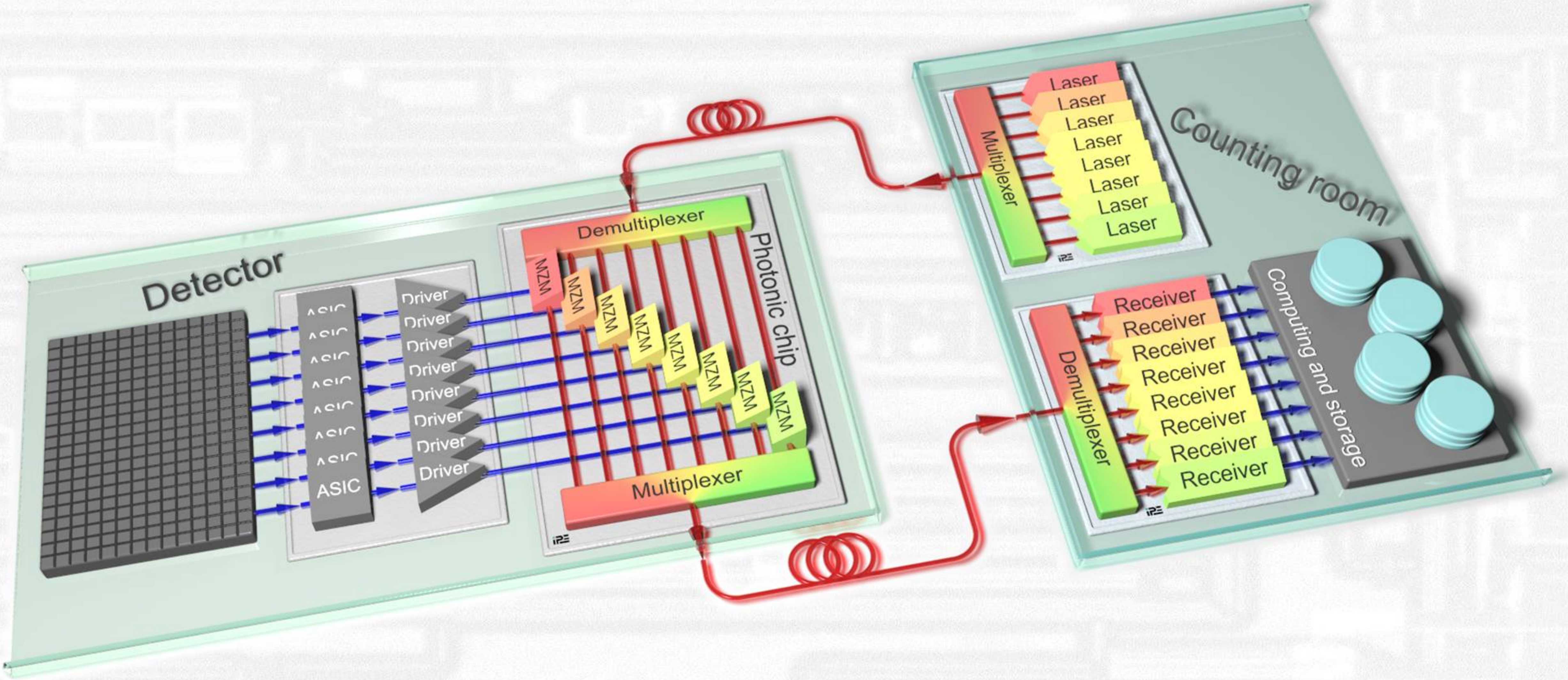
WDM-System

Receiver:

- *Demultiplexer*
- *Photodiodes*

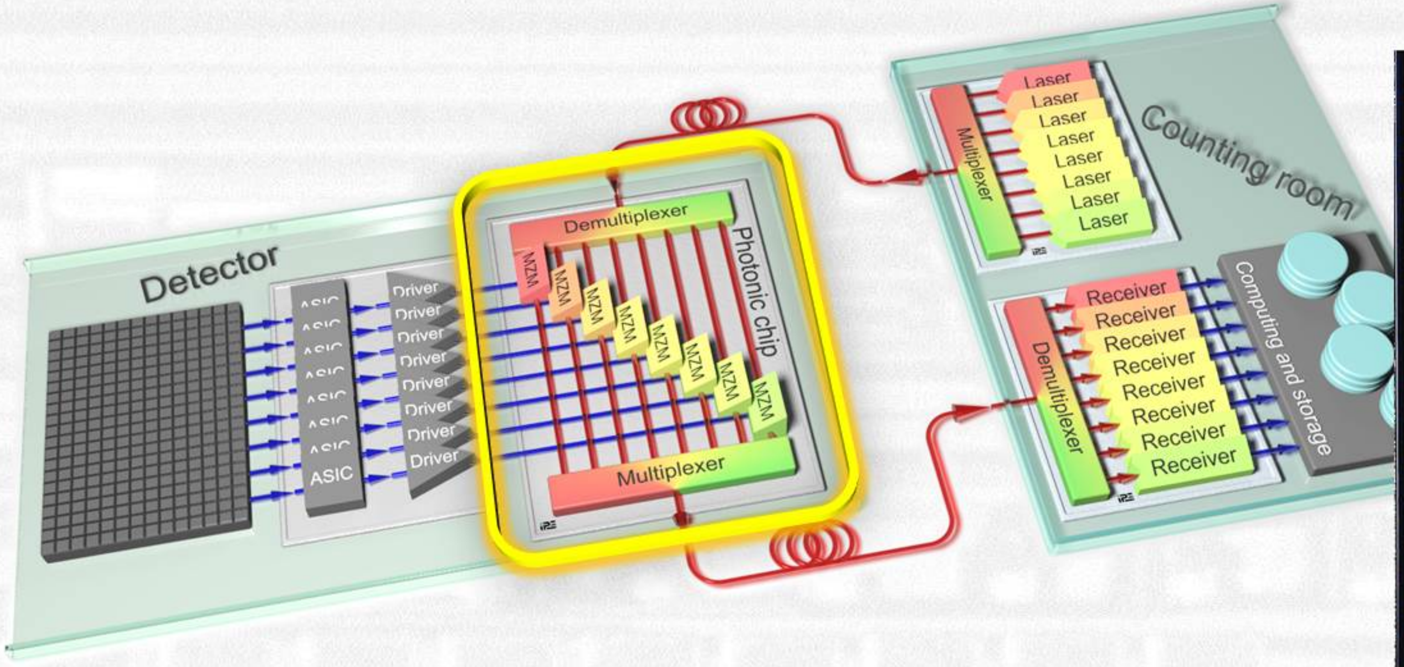


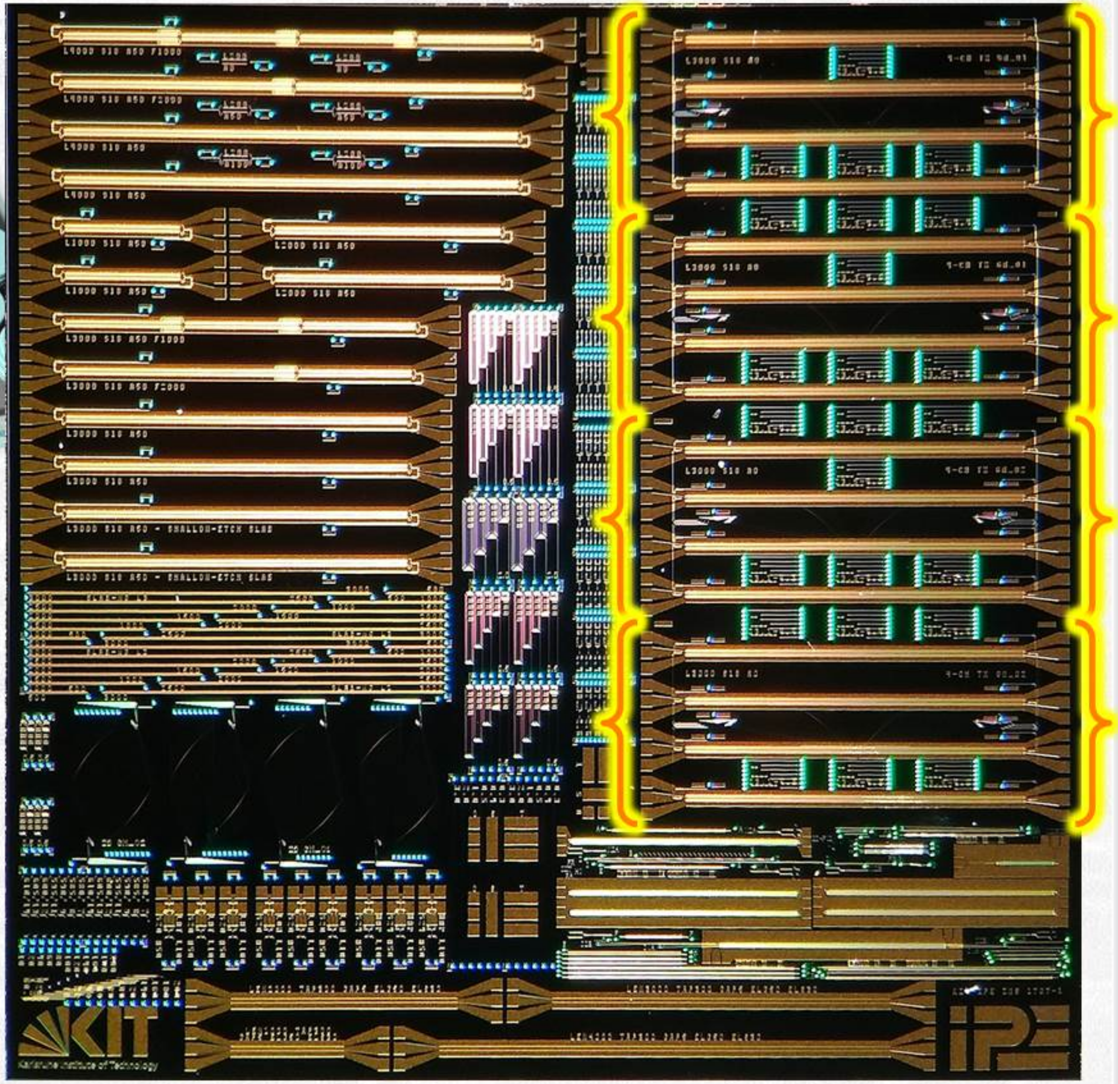
WDM-System



Detector
ASIC
Driver
Photonic chip
Demultiplexer
MZM
Multiplexer
Counting room
Laser
Multiplexer
Receiver
Demultiplexer
Computing and storage

WDM-System

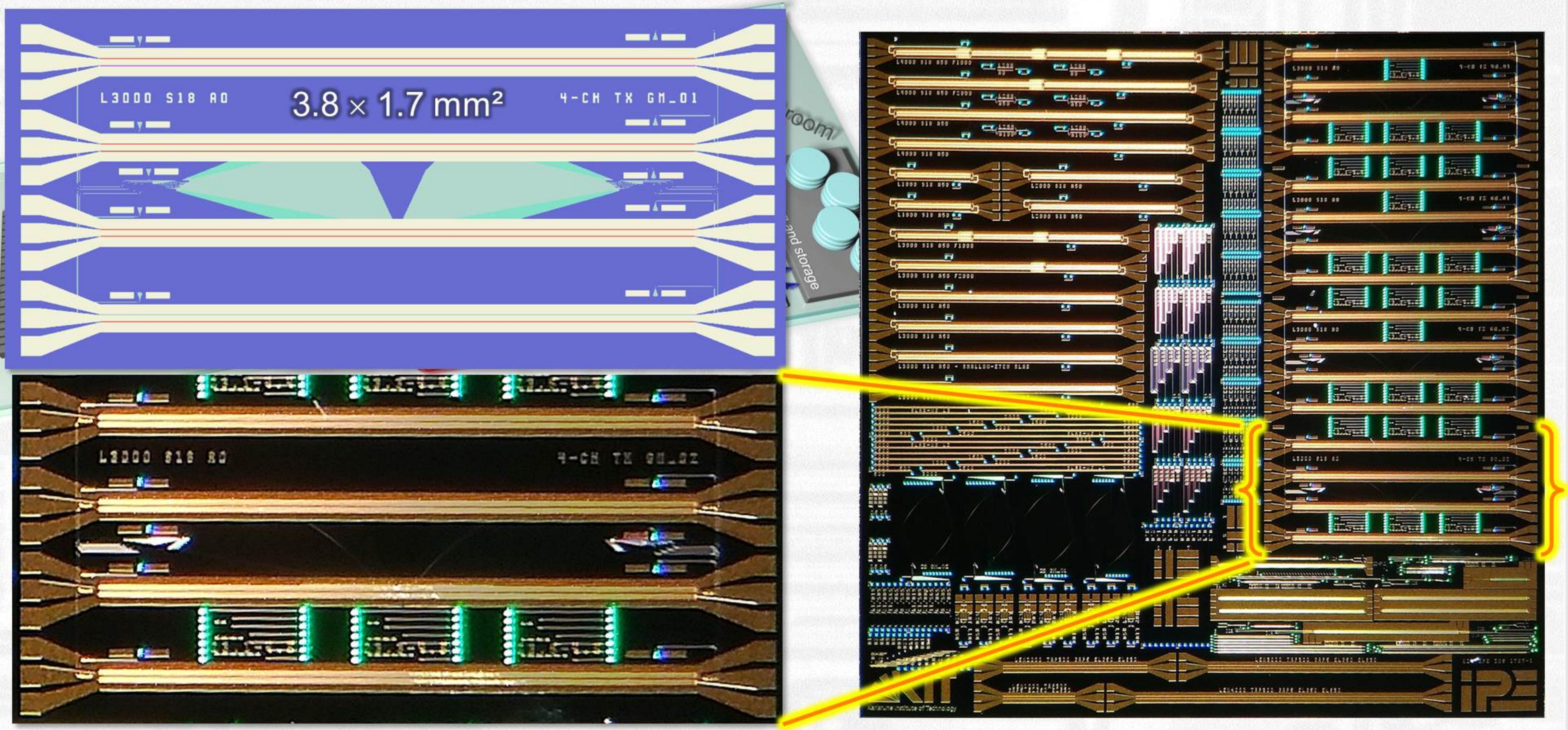




4-channel WDM system (current work)

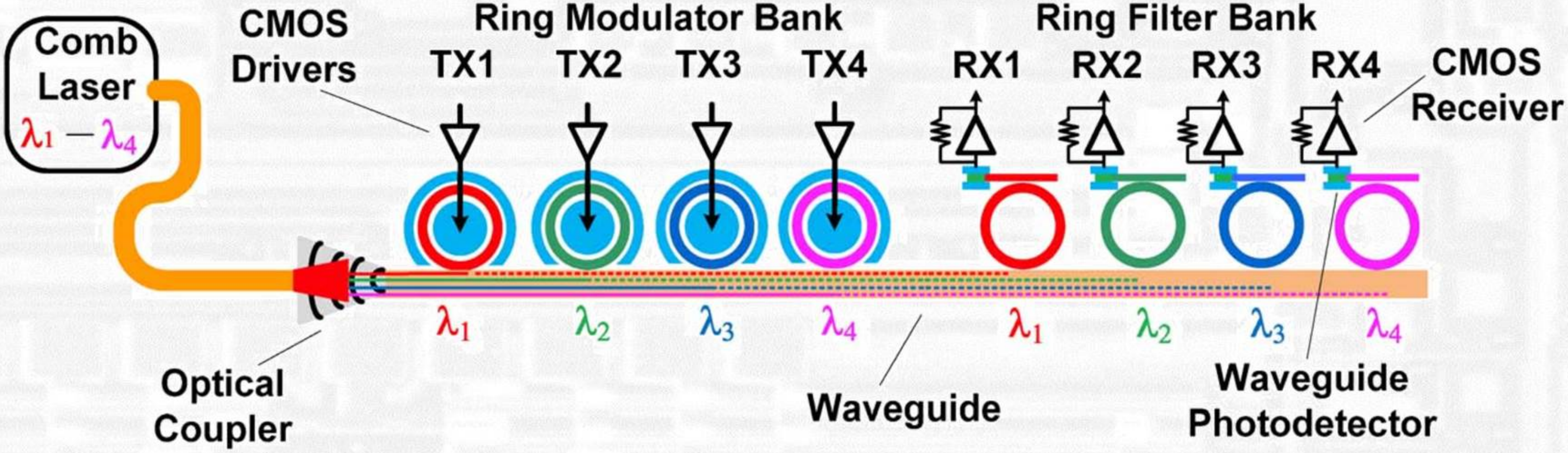
- Échelle grating demultiplexer
- 4 individual Mach-Zehnder modulators
- Échelle grating multiplexer

WDM-System



WDM-System

Future (?): cascaded ring modulators



C. Li et al., IEEE Journal of Solid-State Circuits, Vol 49, No 6, pp1419-1436

- *Pro: much smaller than MZM*
- *Pro: no special wavelength (de-)multiplexers needed*
- *Con: very sensitive to fabrication tolerances*
- *Con: very sensitive to temperature changes*

WDM-System

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Why should we build that?

- *First prototype aims at 4 × 10 Gb/s = 40 Gb/s*
  - *Not much compared to telecom industry, but not bad for HEP…*

Future enhancements:

- *40 Gbaud modulators*
- *PAM4: 2 bits/symbol*
- *32 wavelength channels*
- *2 polarization states*
- *40 × 2 × 32 × 2 Gb/s = 5120 Gb/s ≈ 5 Tb/s seams feasible*

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and… how to use a photonic chip?

⇒ Photonic packaging

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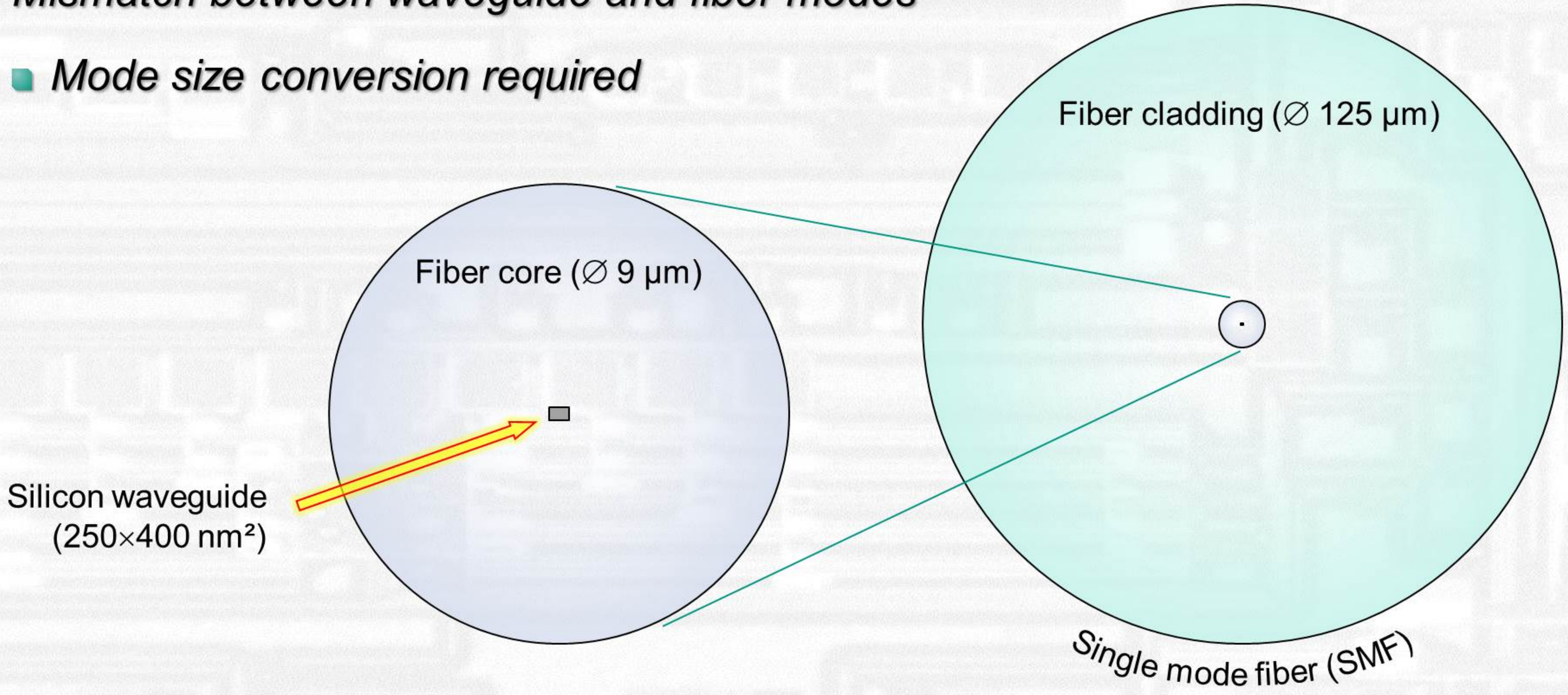
Optical probing of silicon photonic components

Karlsruhe Institute of Technology

Mismatch between waveguide and fiber modes

- Mode size conversion required



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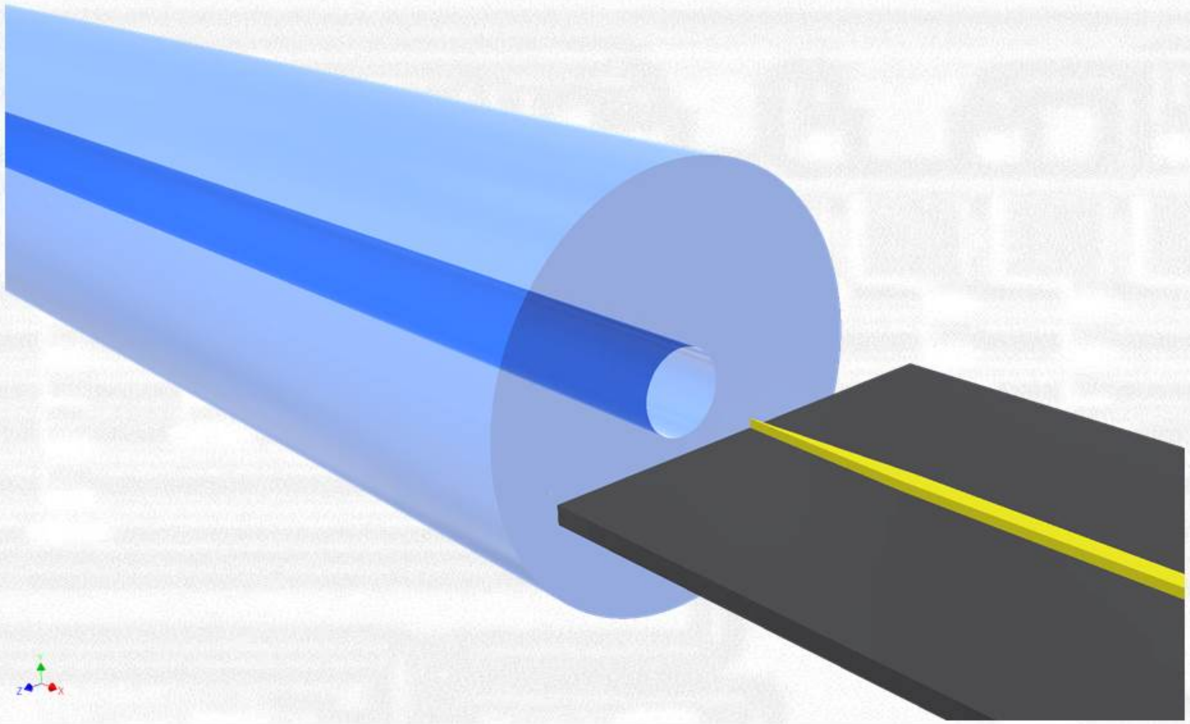
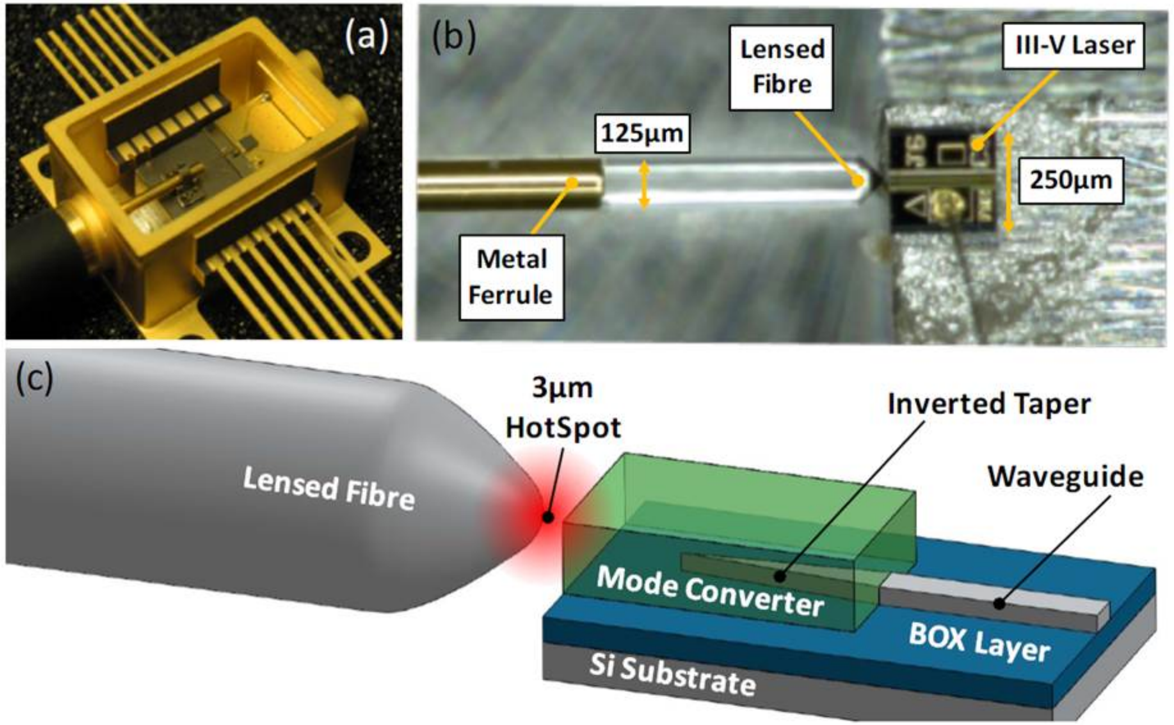
Optical probing of silicon photonic components

Mismatch between waveguide and fiber modes

- *Mode size conversion required*
- *Edge-coupled inverted tapers*



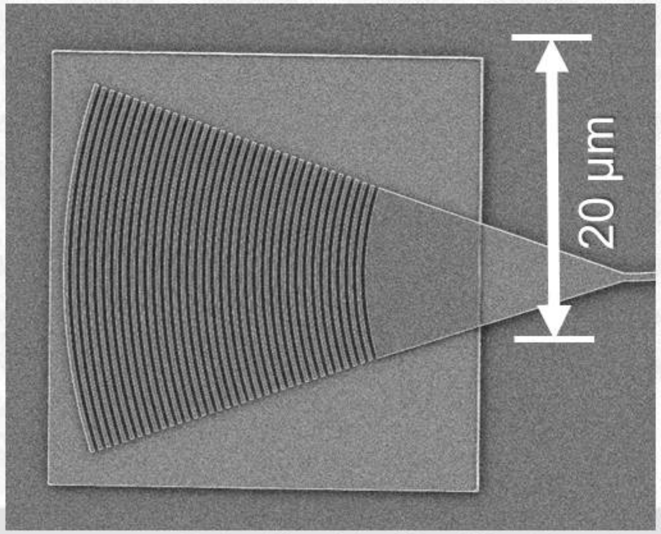


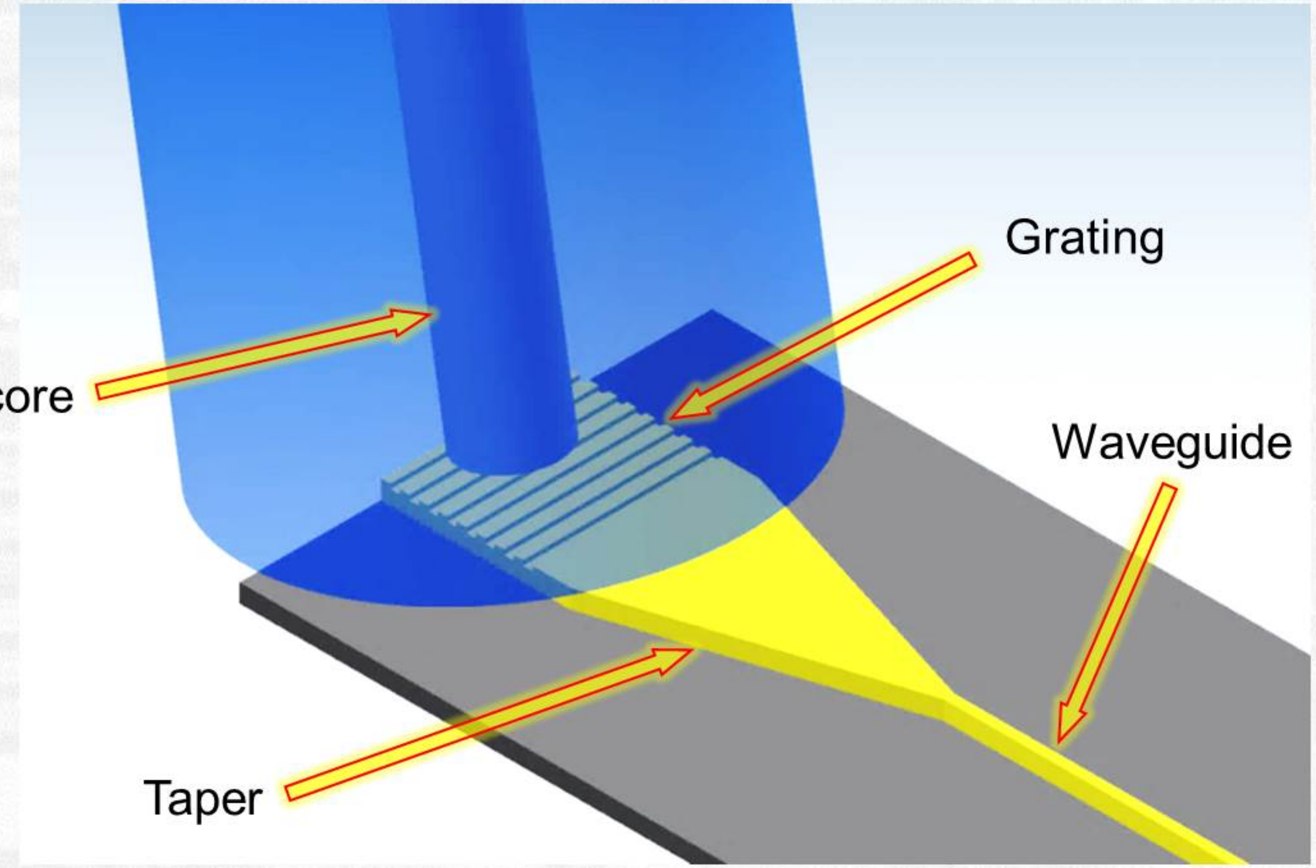
L. Carroll et al., Appl. Sci. 2016, 6(12), 426; doi:10.3390/app6120426

Optical probing of silicon photonic components

Mismatch between waveguide and fiber modes

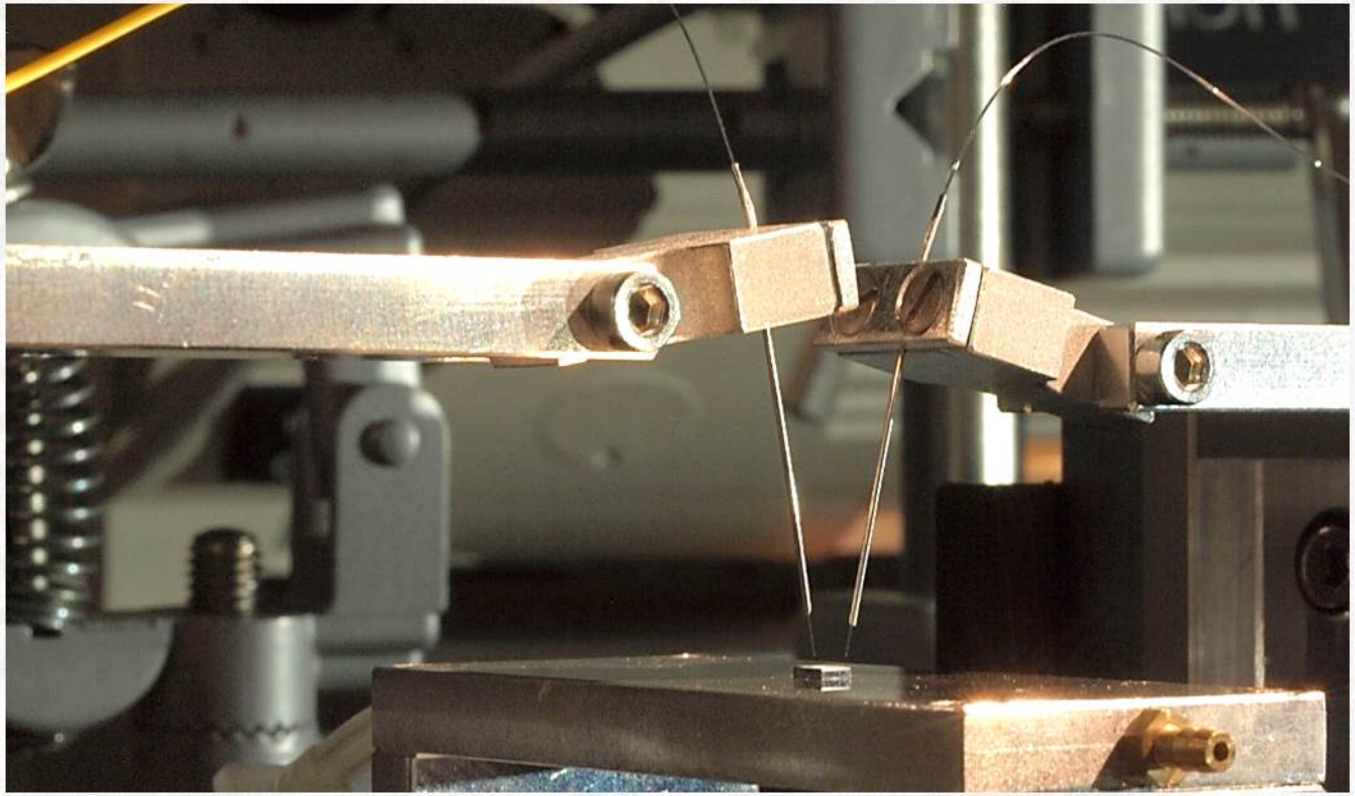
- *Mode size conversion required*
- *Edge-coupled inverted tapers*
- *Grating couplers for surface coupling*





Optical probing with grating couplers

- *Coupling at small angle with respect to the chip surface normal*
- *Mode-size conversion with taper between grating and waveguide*
  - *Pro: Coupling anywhere on chip*
  - *Pro: Low insertion loss*
  - *Con: Spatial requirements oppose dense integration*



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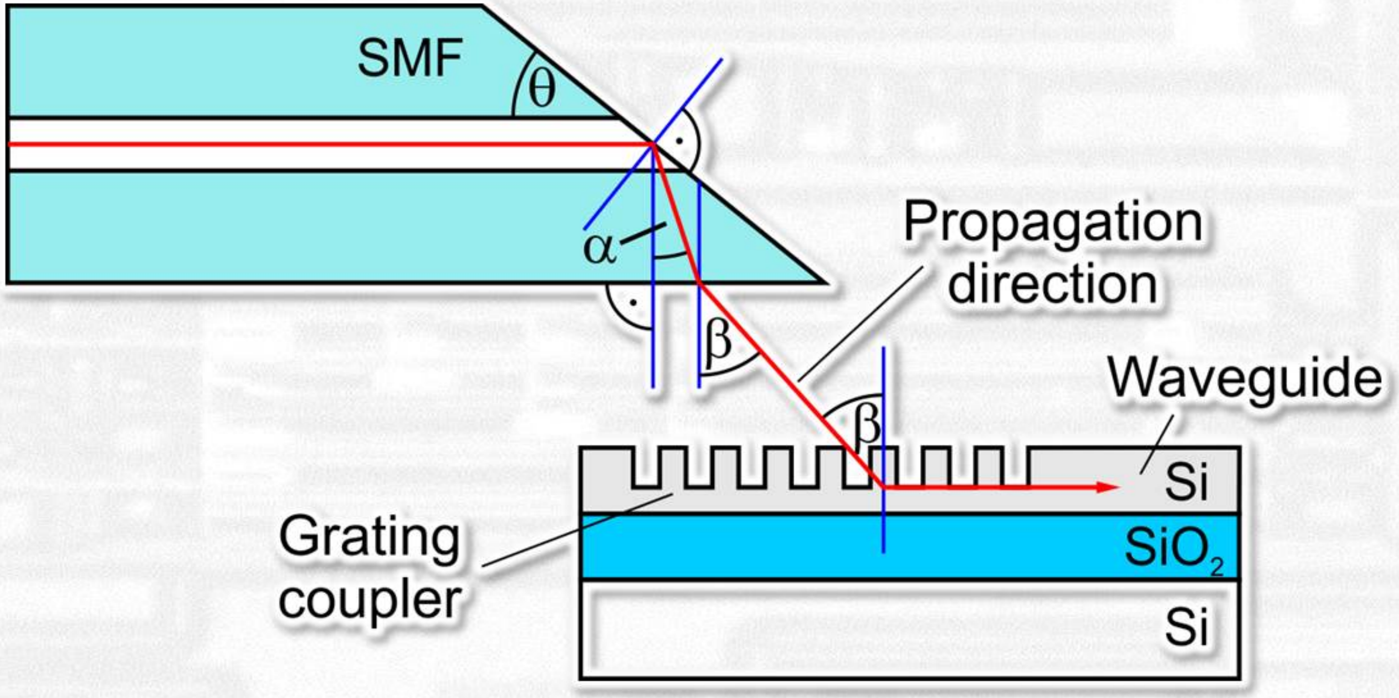
In-plane fiber-chip coupling

- Fiber axis aligned in parallel to chip surface
- SMF is polished at an angle θ smaller than 45 °
- Total internal reflection: Optical field couples radially from SMF to grating coupler



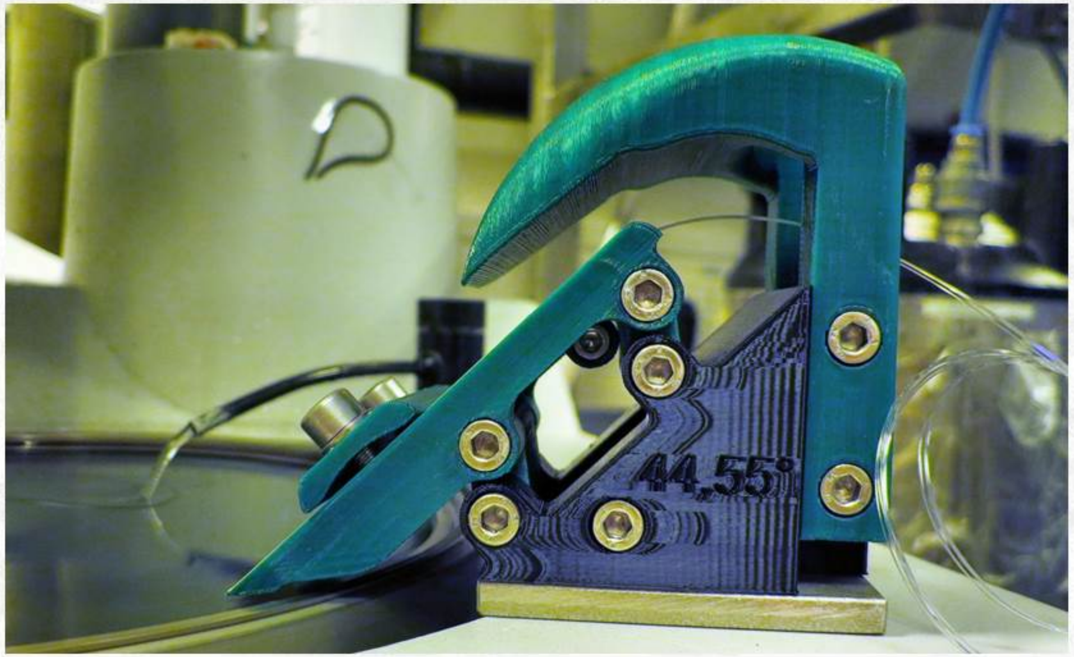
Fabrication of angle-polished fibers

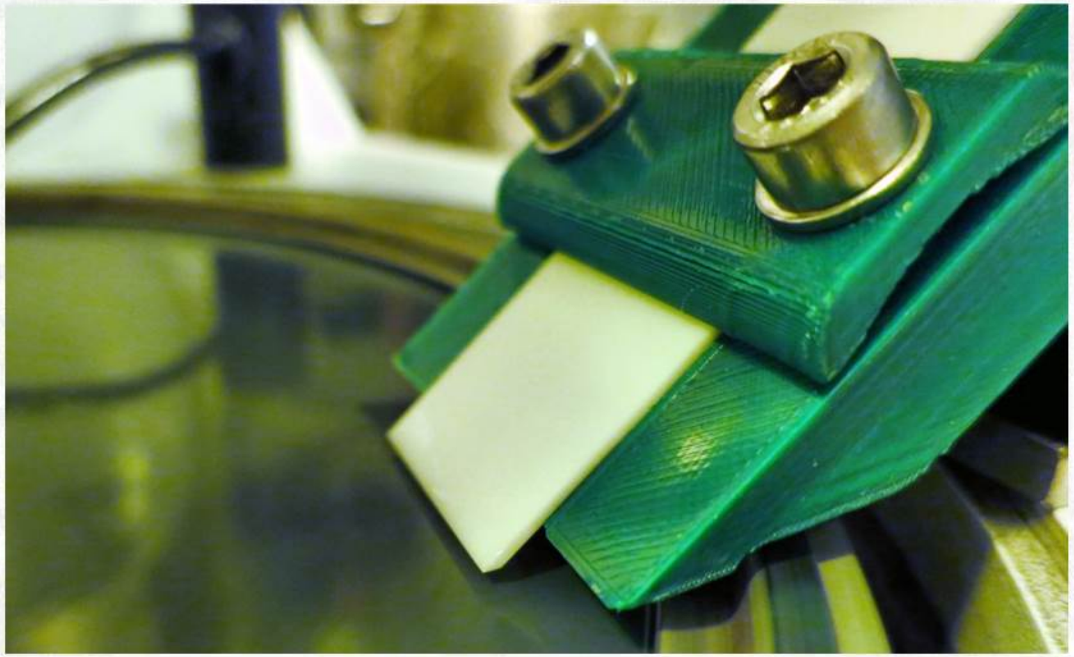
Set polishing angle

- Specially designed fiber holder
- Gauge to select polishing angle
- Fibers fixed on ceramic tile

Polishing of fiber facet

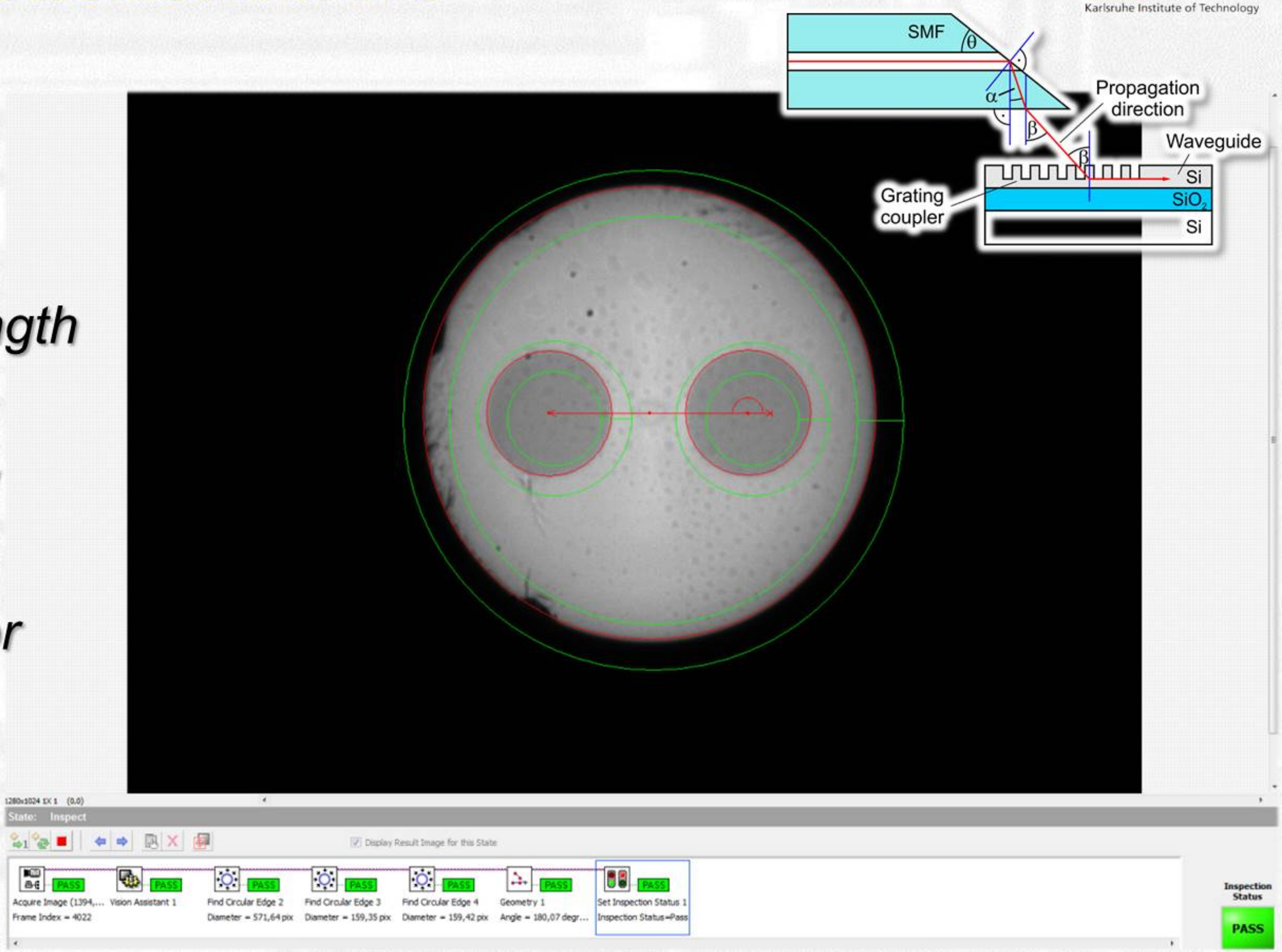
- Rotating grinding/polishing machine
- Coarse shaping with abrasive paper
- Polishing with diamond suspensions





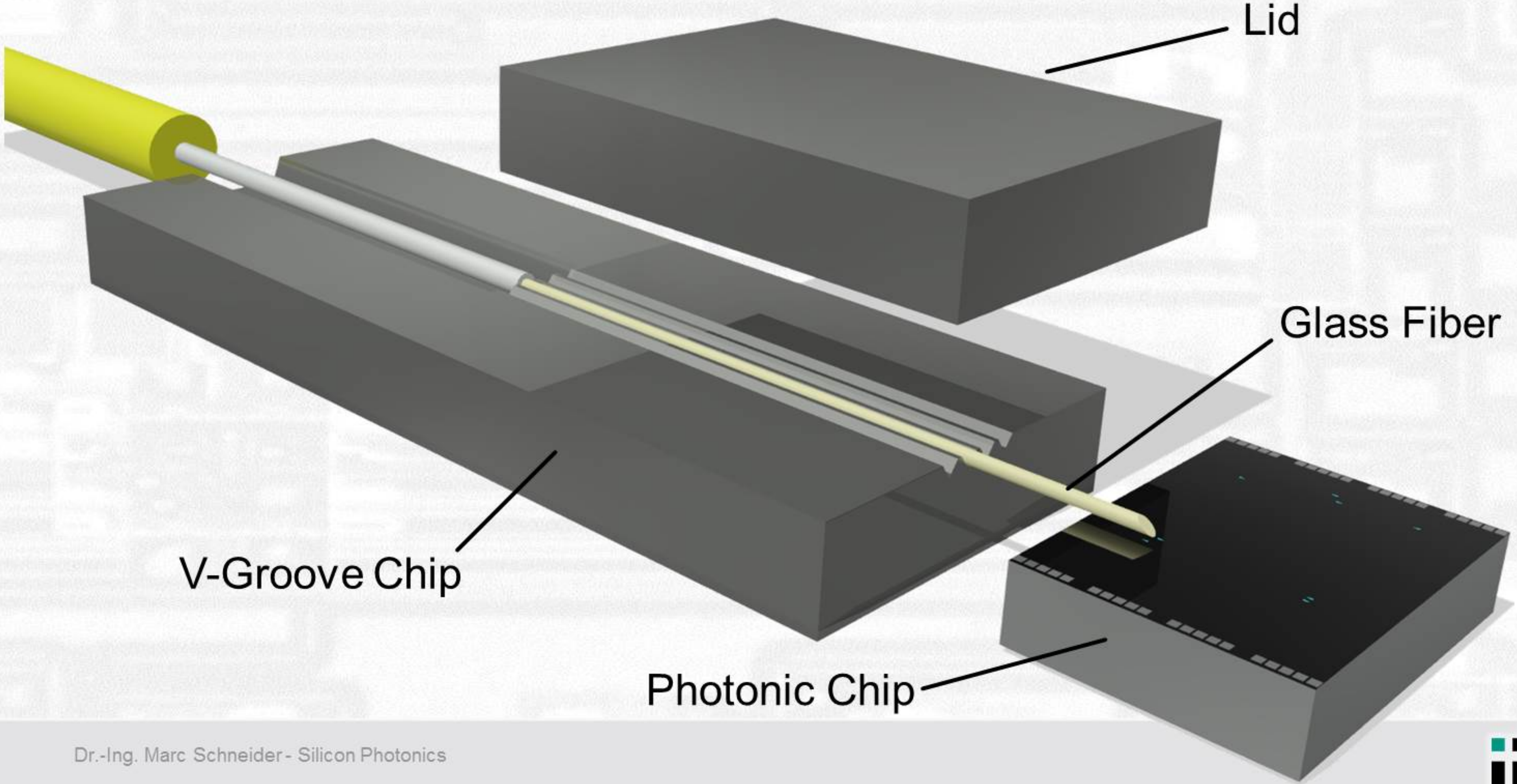
Fabrication of angle-polished fibers

- Grating couplers are polarization sensitive
- For WDM the correct polarization of each wavelength channel has to be ensured
- Use polarization maintaining fibers
- Ensure correct orientation for angle polishing



Mounting polished fibers

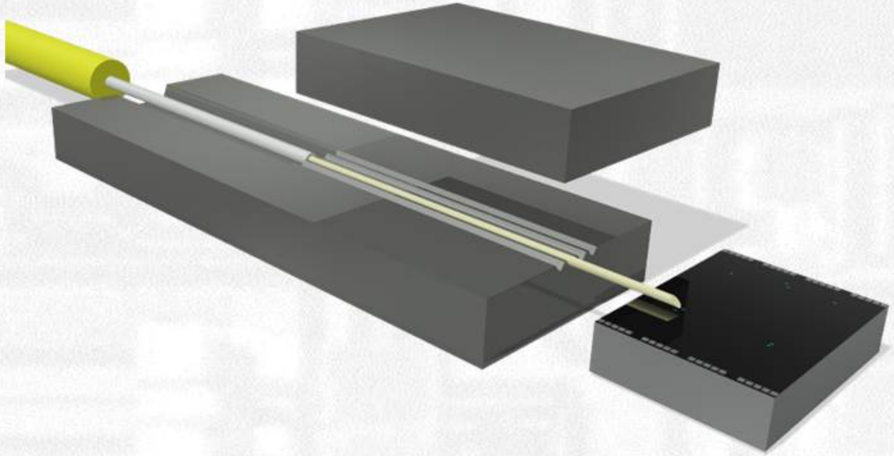
- *Mounting of polished fibers on standard glass v-groove chips*
- *Fixation with UV-curing adhesive*

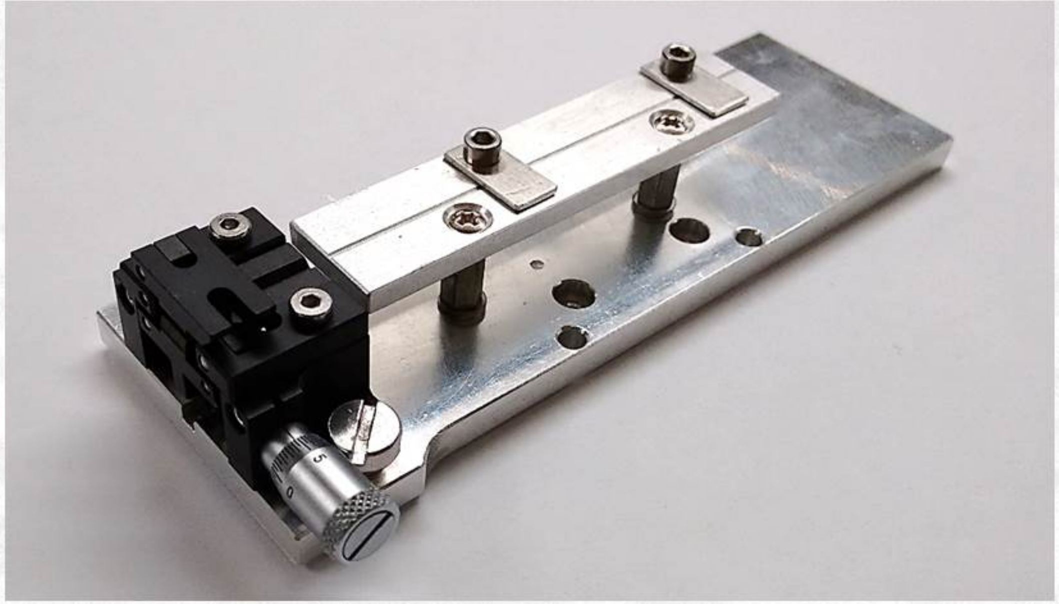


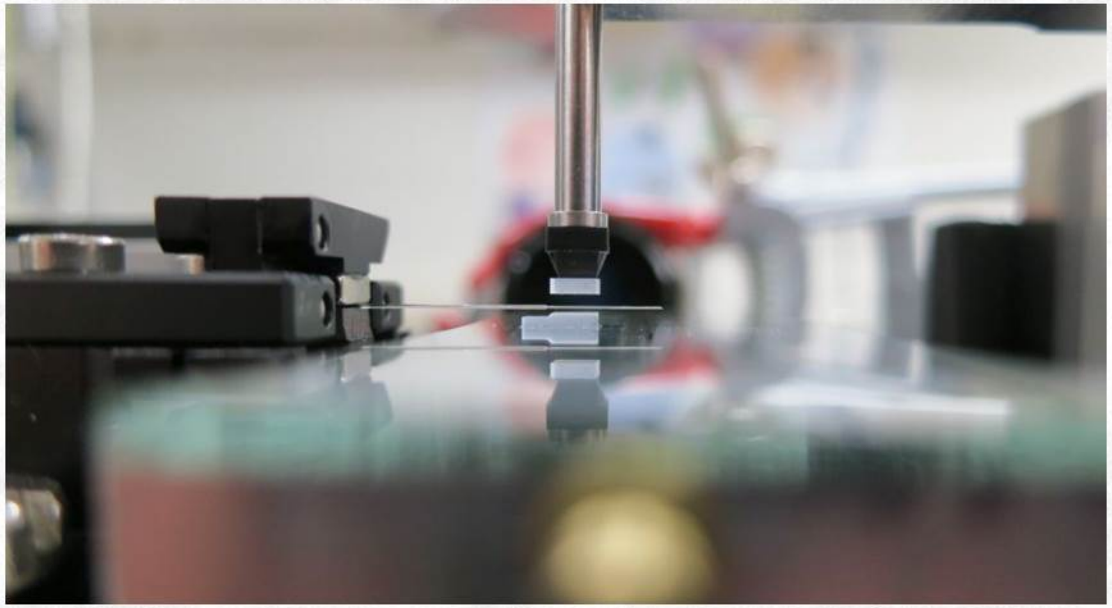
Optimization of fiber rotation

Additional degree of freedom

- Adjustment with mechanical fiber rotator
- Optimization for maximum coupling efficiency
- Reference: grating-coupled test structure





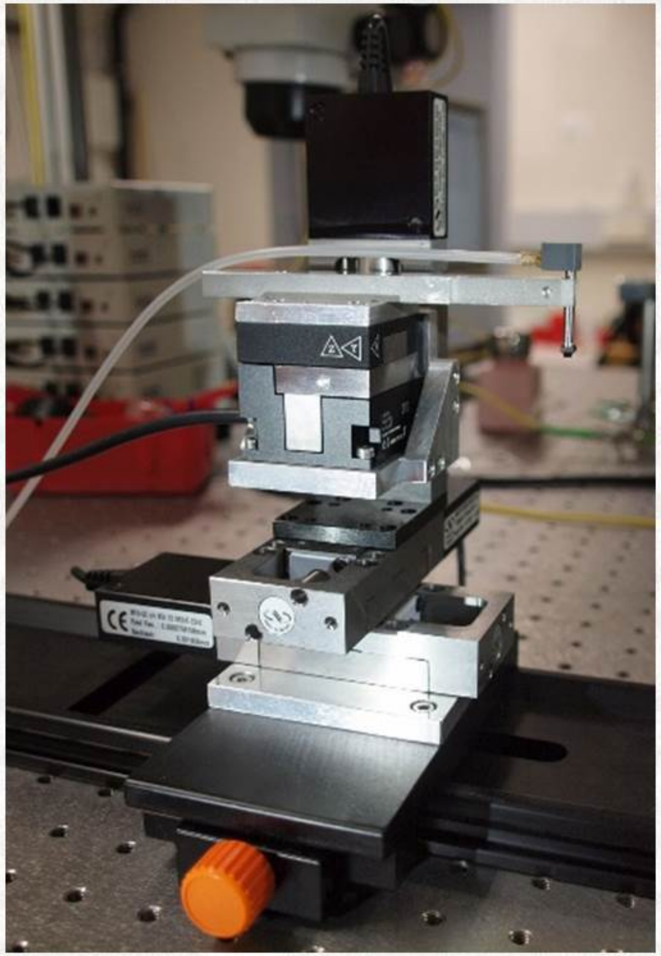


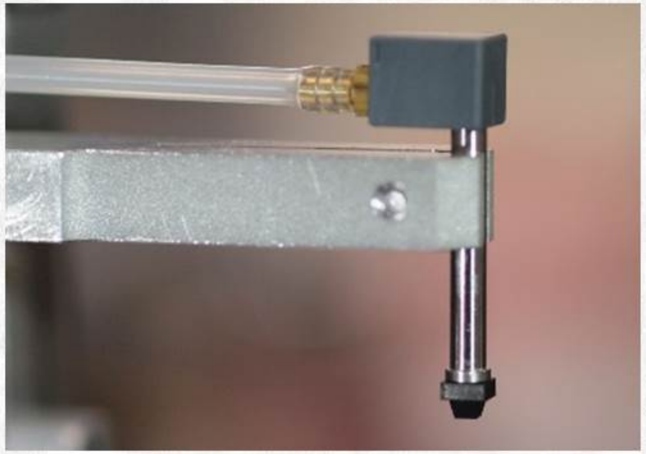
Assembly of the arrangement

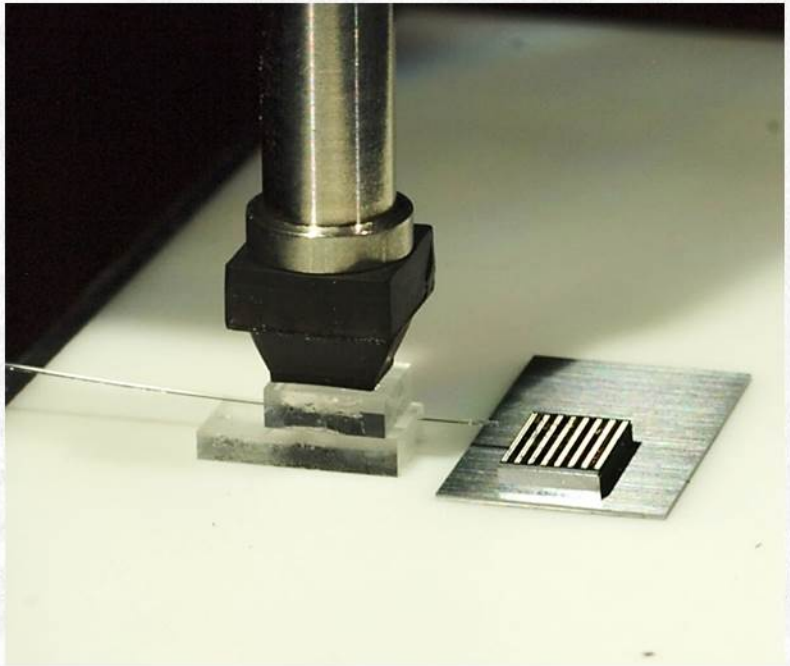
Precision alignment equipment
- Enhanced fiber probing setup
- Stepper motors and piezo-stages
- Custom vacuum pick-up holders
- Standard rubber tips

Placement
- Bonding of photonic chip to substrate
- Elevation by silicon spacer
- Active alignment by manual positioning of V-groove chips

Fixation
- V-groove chips fixed on substrate with UV-curing adhesive

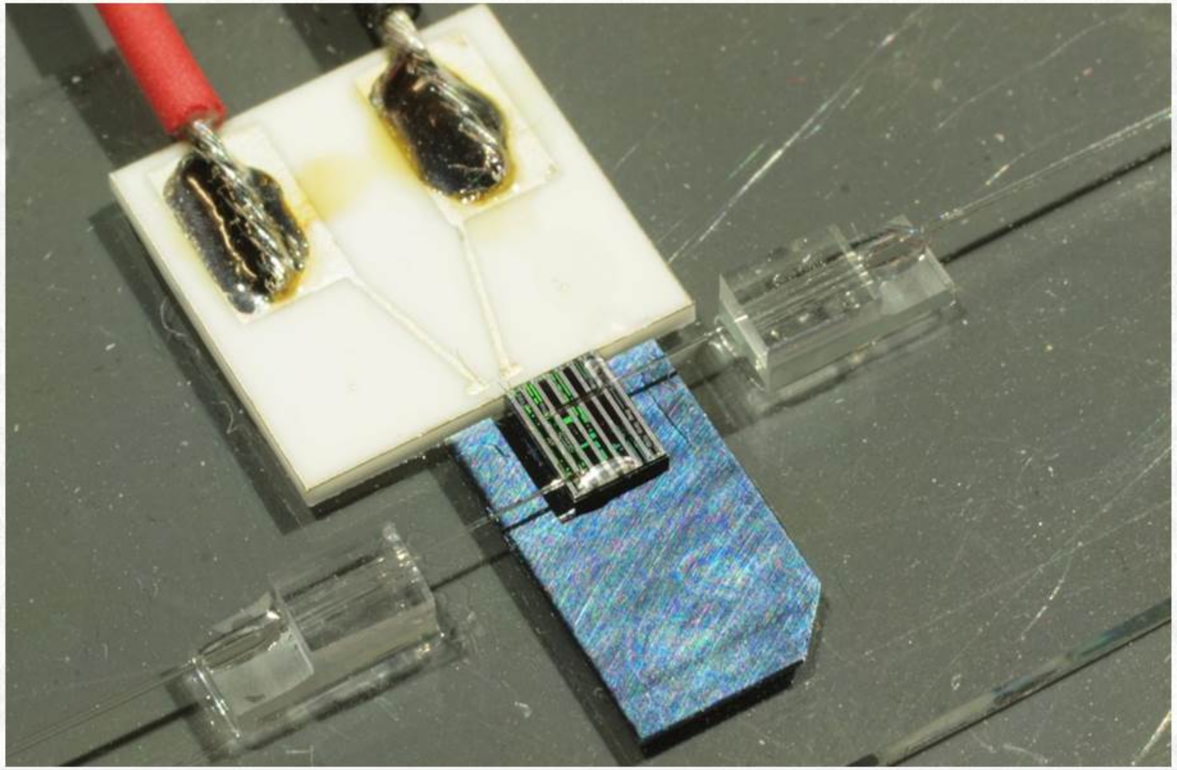


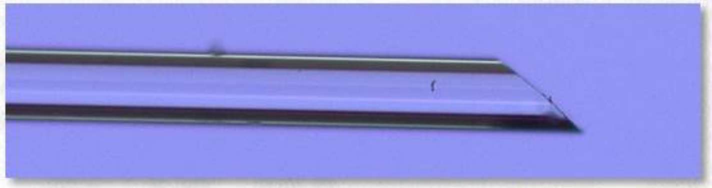


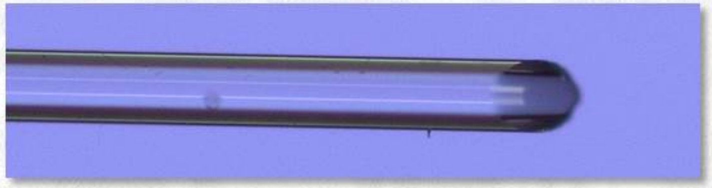


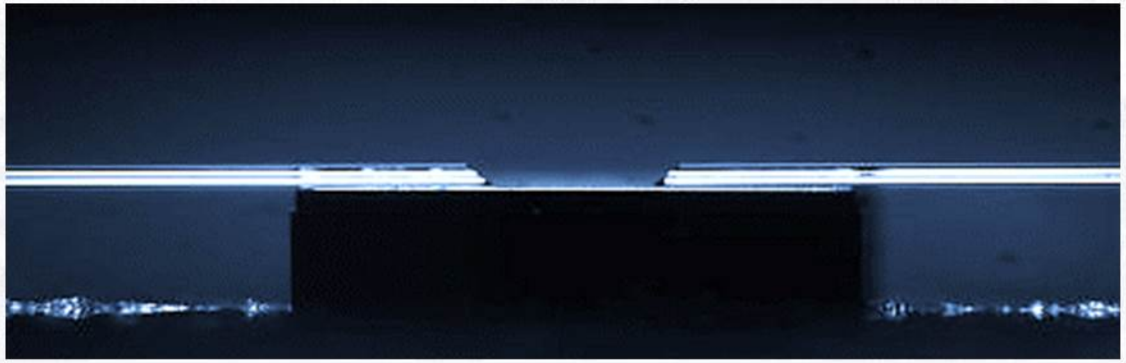
Assembly of the arrangement

- Electrical pads of the chip are wire-bonded to ceramic conductor board
- Mechanical stability improved by bonding the fibers also to chip surface
- No penalty on coupling efficiency upon UV-curing observed









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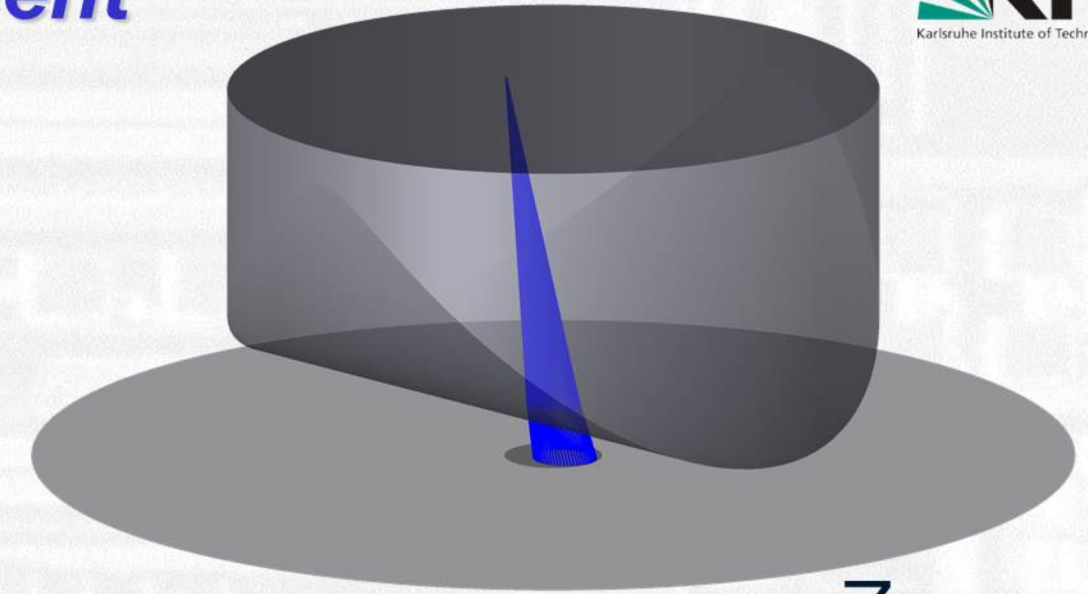
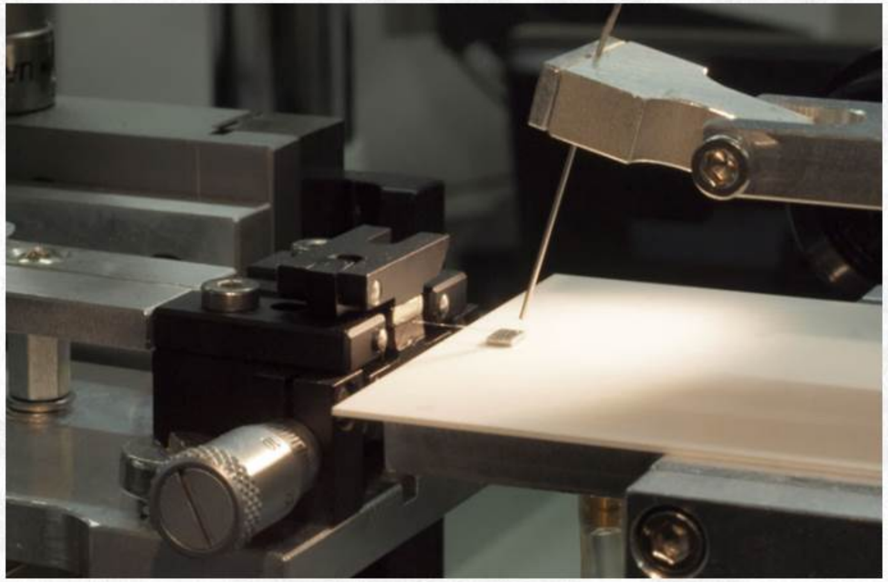
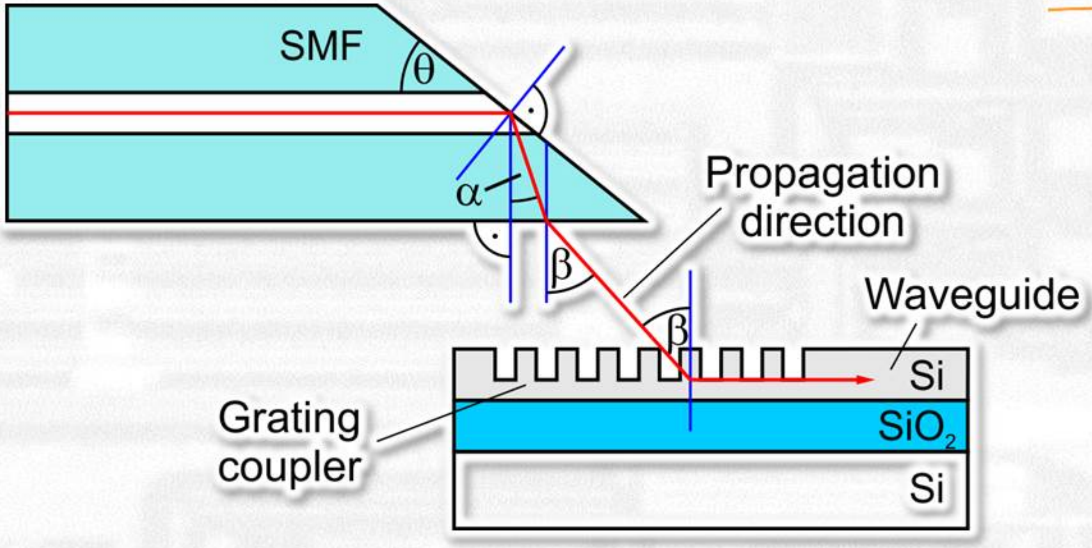
Validation of coupling arrangement

Alignment tolerances

- *Coupling efficiency depends on displacement of fiber from optimum*
- *Simulation with Zemax OpticStudio*
- *Experimental verification*

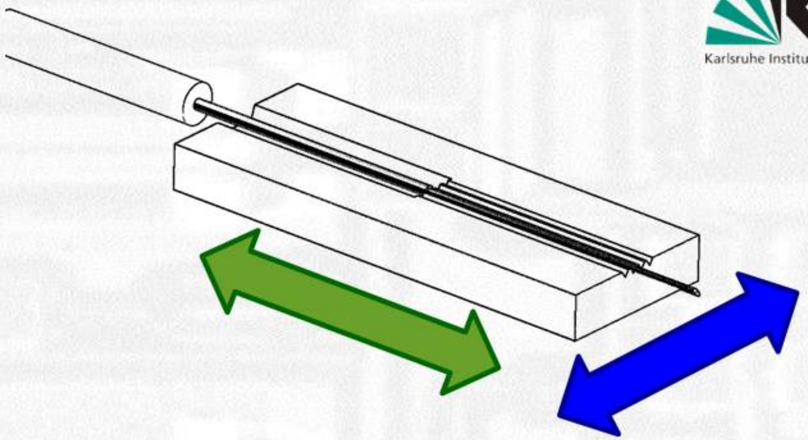


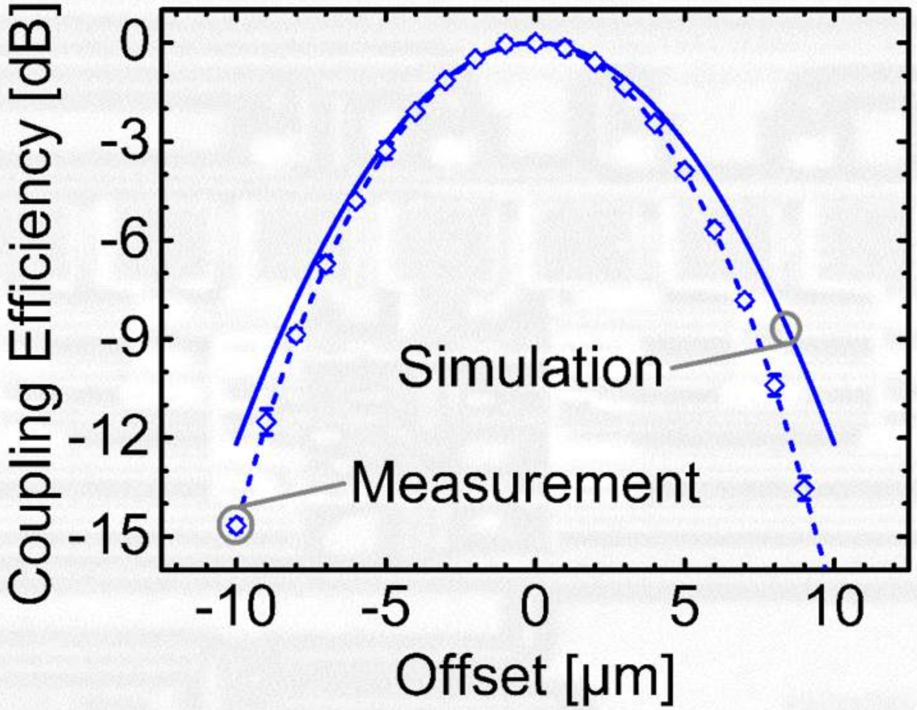


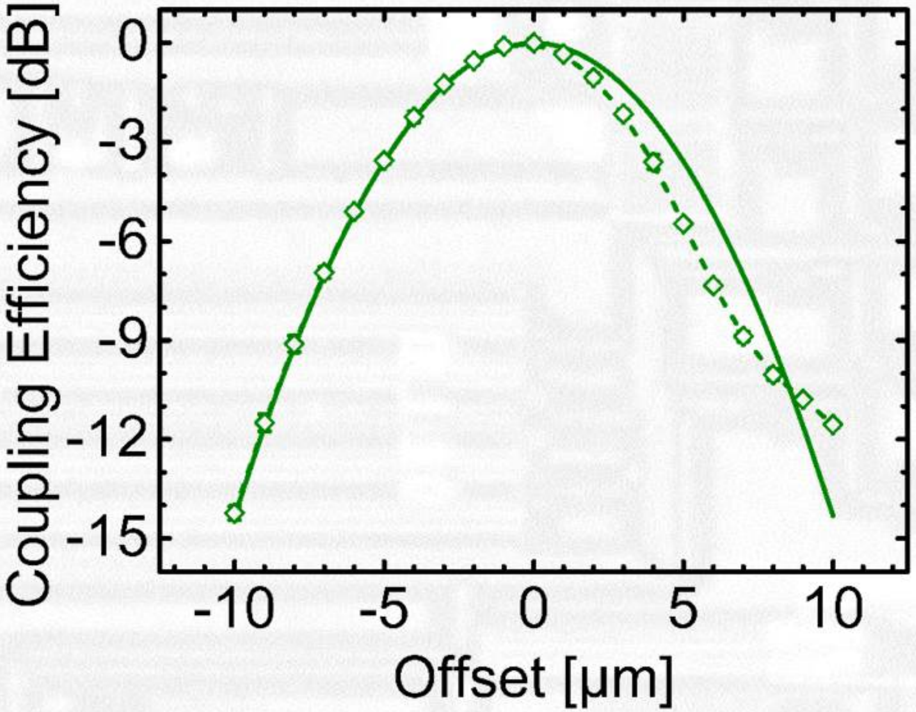


Alignment tolerances

- *Coupling efficiency depends on areal displacement from optimum*
- *±4.5 µm offset tolerable for 3 dB penalty*

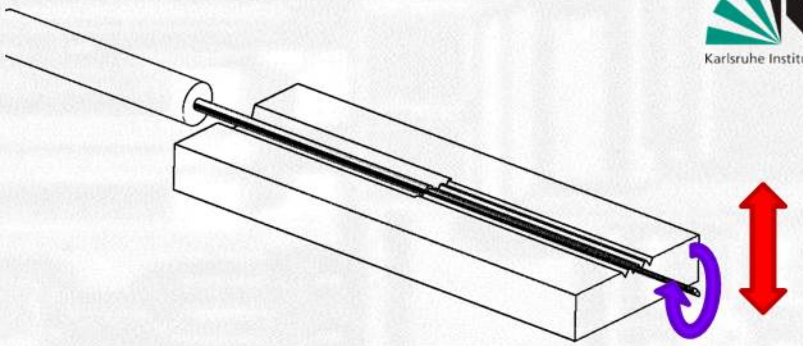


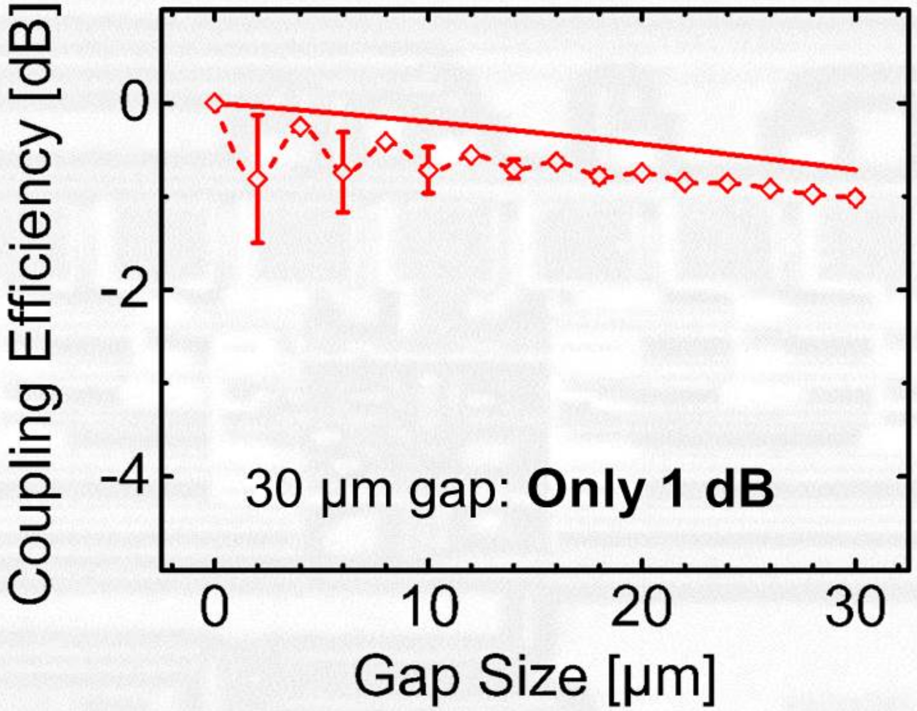


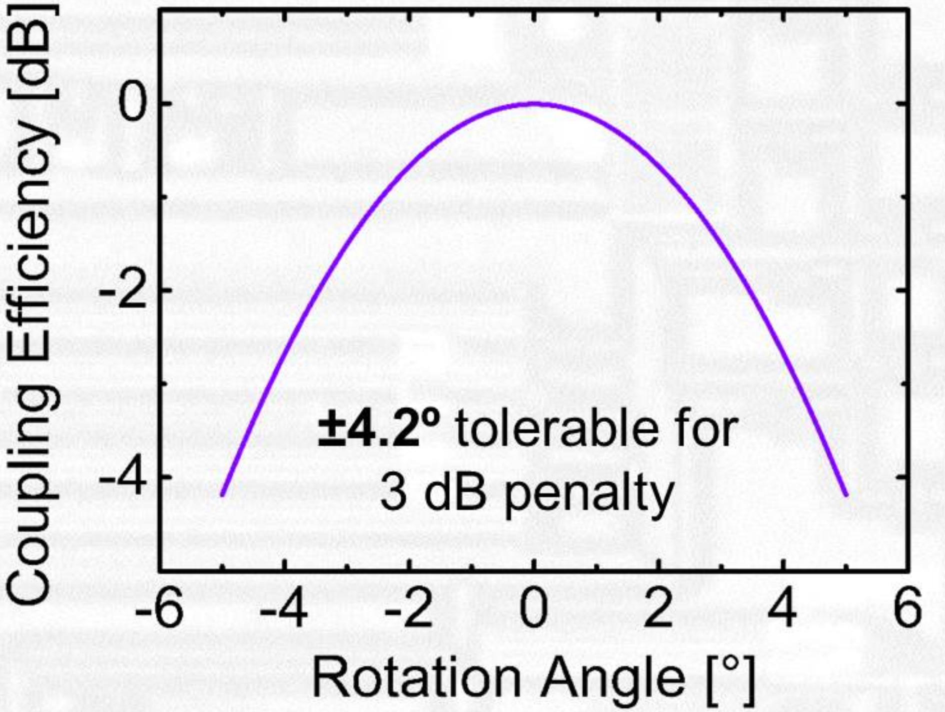


Alignment tolerances

- *Coupling efficiency depends on gap size between fiber and grating coupler as well as fiber rotation angle*



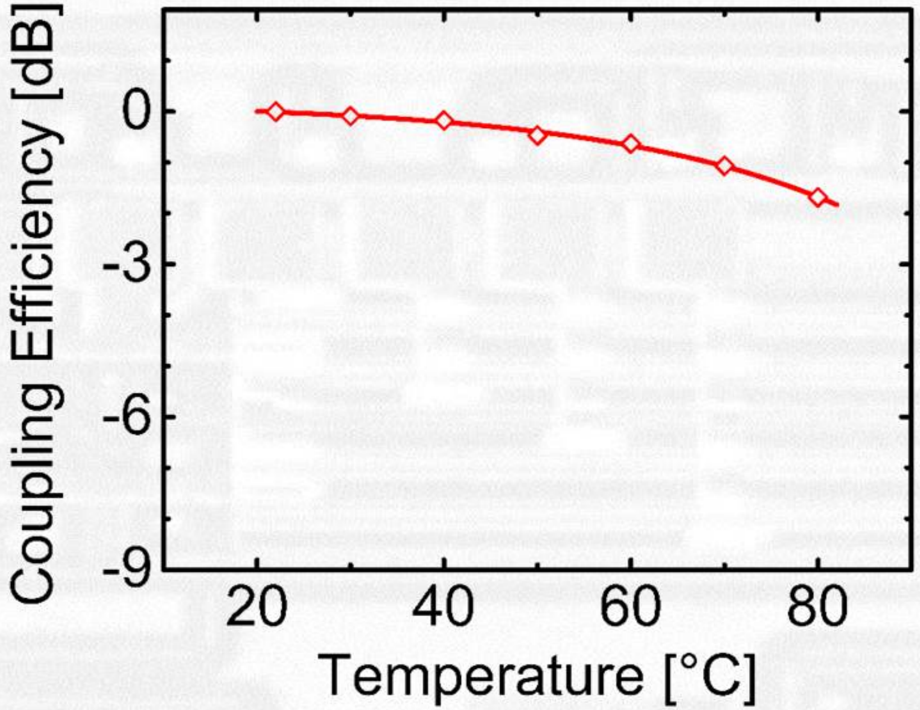


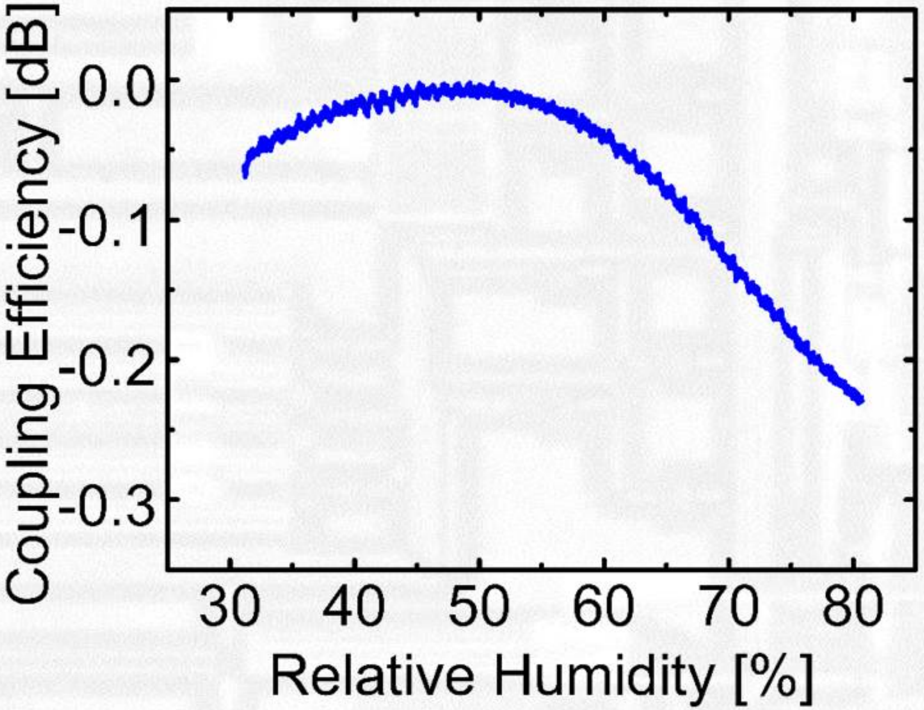


Coupling stability

Climate testing cabinet

- *Temperature 20…80 ºC @ relative humidity 30%: Penalty < 2 dB, reversible*
- *Relative humidity 30…80% @ temperature 20 ºC: Penalty ≈ 0.2 dB, reversible*





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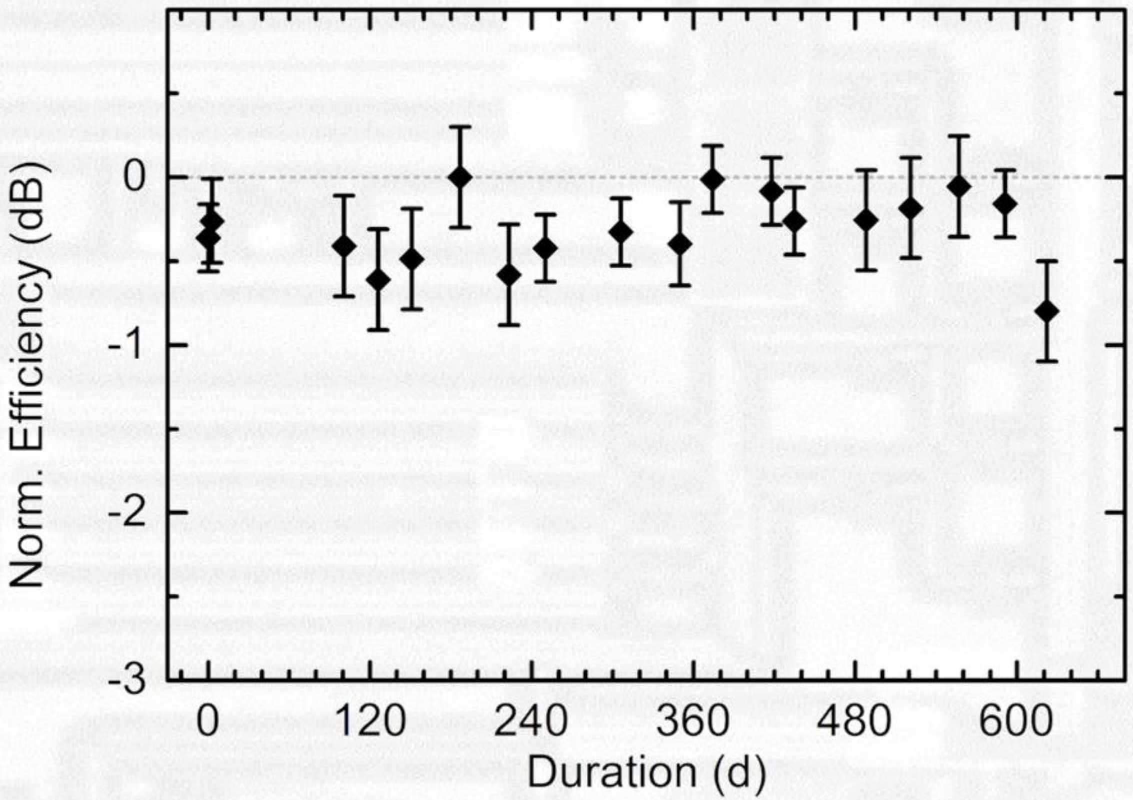
Coupling stability

- *Coupling efficiency in non-stabilized environment*
- *Measured optical power normalized to highest value*
- *No significant loss*
  over almost two years

→ **long-term stable**



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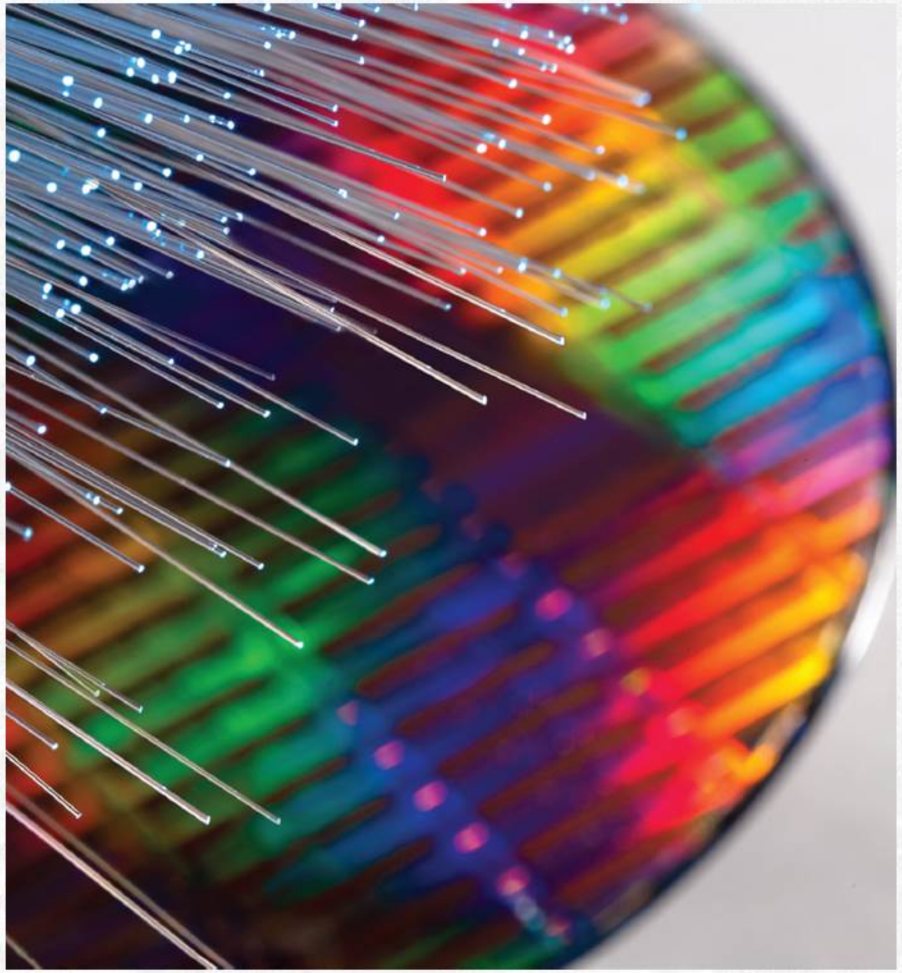
Summary

- Silicon Photonics
  - History
  - Material
  - Components (waveguides, photodiodes, modulators, (de-)multiplexers)
  - WDM Systems
- Photonic packaging
  - Mode size converters and coupling methods
  - In-plane coupling through angle polished fibers



https://cacm.acm.org/magazines/2016/5/201588-silicon-photonics/fulltext

Thank you!