Optoelectronics
Research Centre

UNIVERSITY OF
Southampton

# Silicon Photonics: the next revolution in telecom and beyond

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www.siliconphotonics.co.uk

Malaga, 8 May 2018

# Outline

- ORC Silicon Photonics Group
- Why Silicon Photonics
- Collaboration with Malaga
- Final messages

# Silicon Photonics Group

- Established at the University of Surrey in 1989
- Joined University of Southampton in 2012
- 54 people (4 academics)
- 15 projects (£28 million; EPSRC, industry, H2020, RS, RAEng)

## Design

Photon Design®

lumerical

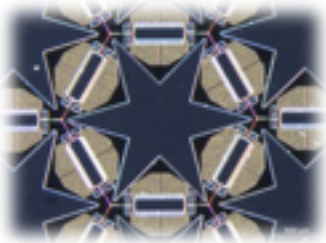
SILVACO

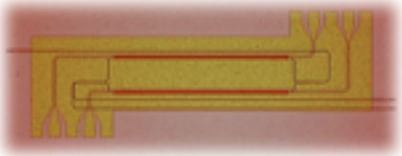
MATLAB

Advanced Design System
Premier High-Frequency and High-Speed Design Platform
KEYSIGHT TECHNOLOGIES

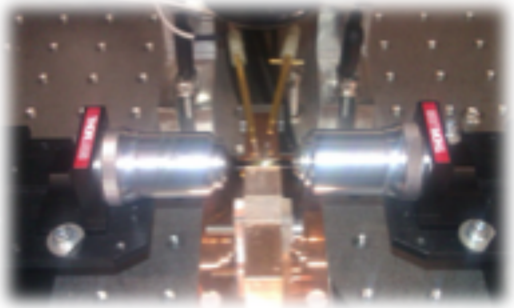
## Fabrication

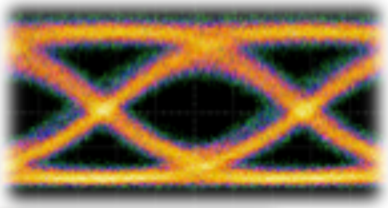
SOUTHAMPTON
NANOFABRICATION CENTRE





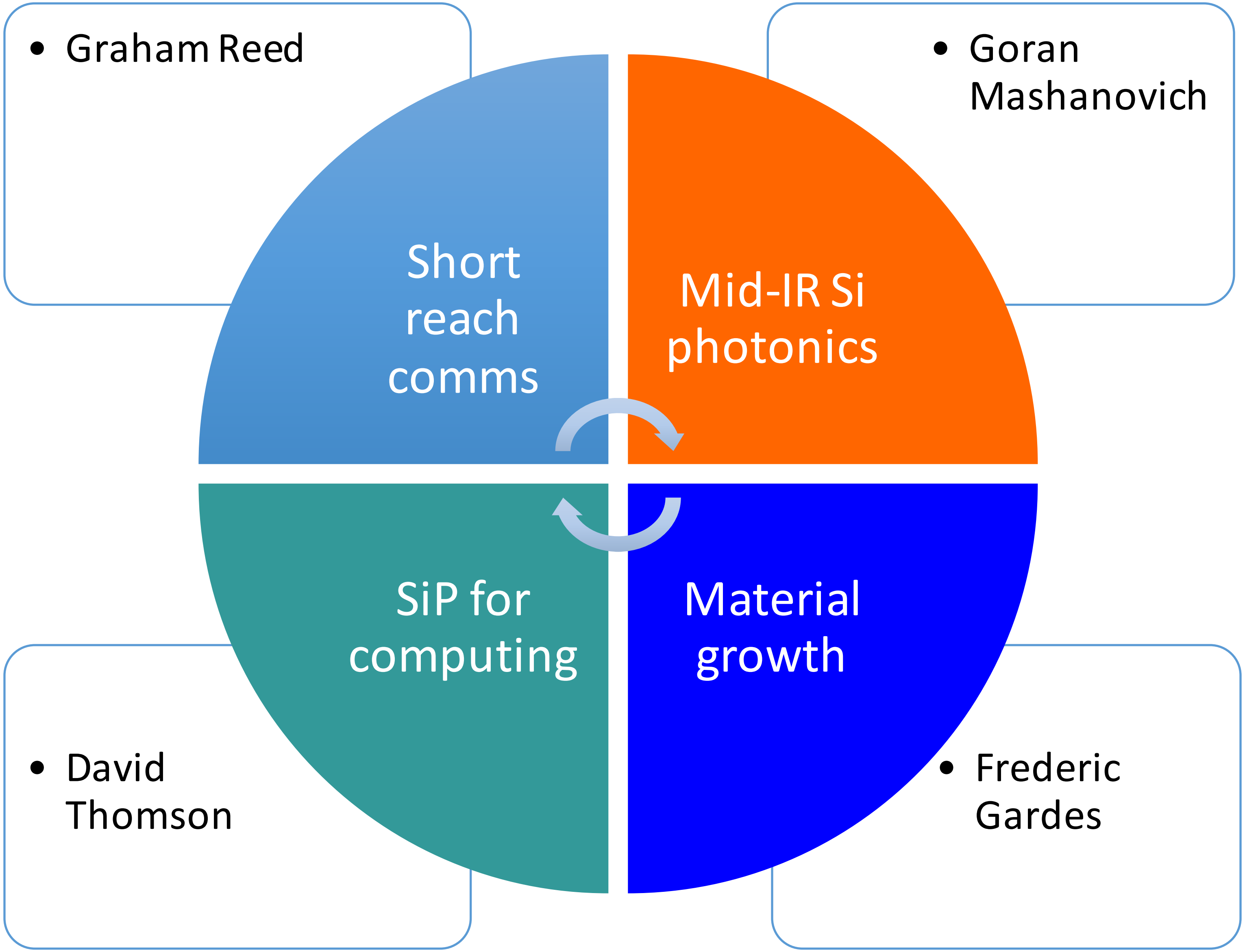
## Characterisation





Silicon Photonics Group

# Silicon Photonics Group



- Graham Reed

- Goran Mashanovich

Short reach comms

Mid-IR Si photonics

SiP for computing

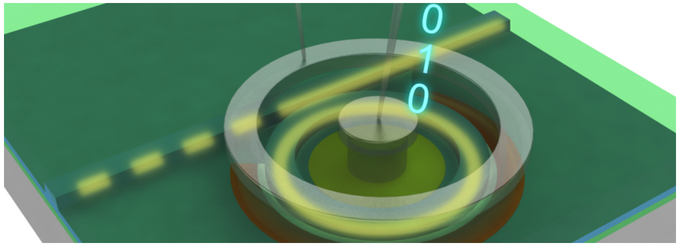
Material growth

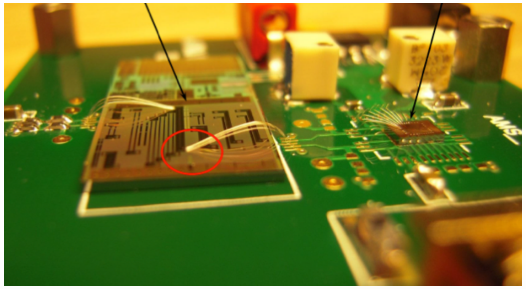
- David Thomson

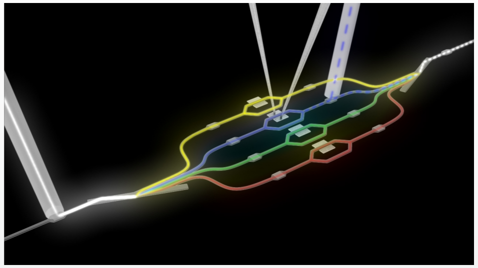
- Frederic Gardes

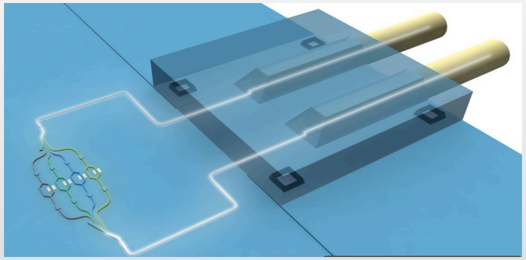
# Silicon Photonics Group - Research

- Low loss waveguides (1.3 – 12 μm)
- Couplers, splitters, filters, interferometers, switches
- (DE)MUX
- Optical modulators, photodetectors
- Photonic/electronic integration
- Packaging
- Wafer scale testing
- Fabrication, growth, new materials
- Sensors

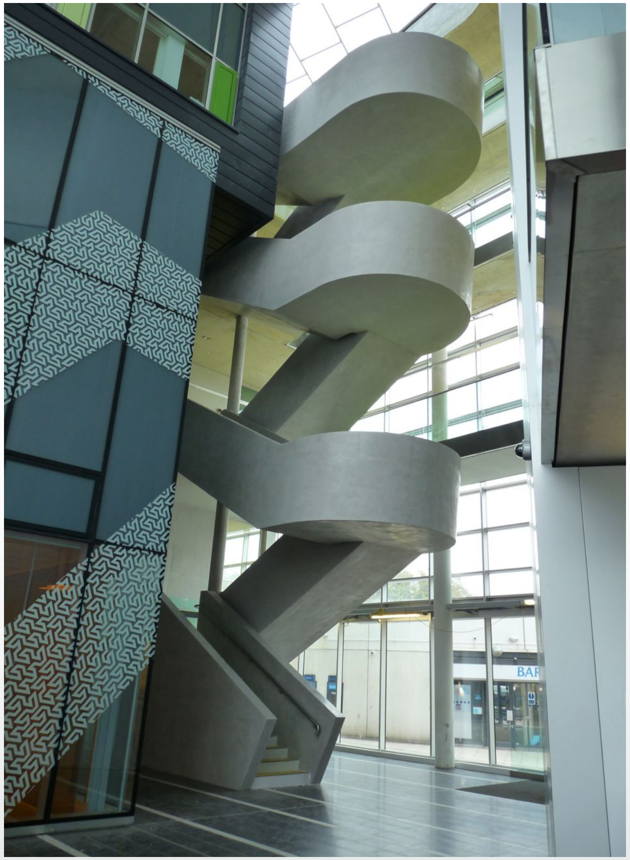








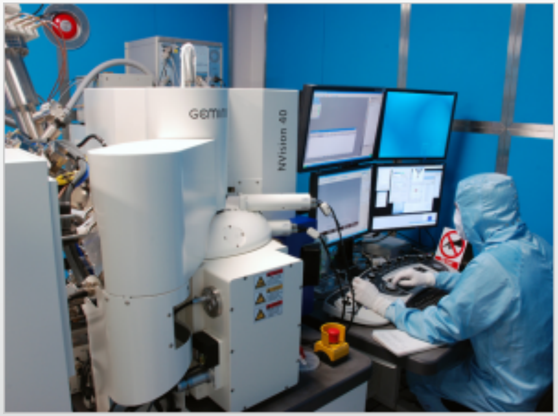
# Optoelectronics Research Centre



- Largest photonics institute in the UK (over 350 staff/PhD)
- £70M of secured research funding
- 90 photonics laboratories
- £100m purpose-built materials and nanofabrication facility, with over 2000m$^2$ of state-of-the-art clean rooms
- 20 patents per year
- A cluster of 12 start-up companies
- Fibres, amplifiers, lasers, planar photonics, sensors, quantum photonics, **silicon photonics**

# Labs and cleanroom

- Sources and detectors from UV to MIR
- In-plane and out of plane coupling setups
- Optical and electrical testing (up to 64 GHz)
- Contact, e-beam and DUV lithography
- Dry (RIE, ICP, DRIE) and wet etching
- Deposition (PECVD, LPCVD, HWCVD, ALD) – a-Si, poly-Si, a-Ge, SiN, SiGe
- Deposition of many other materials (ZnSe, Ta2O5, GeTe, GLS etc)
- Evaporators, sputterers
- Annealers, furnaces
- Dicing
- Wire and flip-chip bonding (40 GHz demonstrated)
- SEM, AFM, XRD, surface profilers, FIB etc



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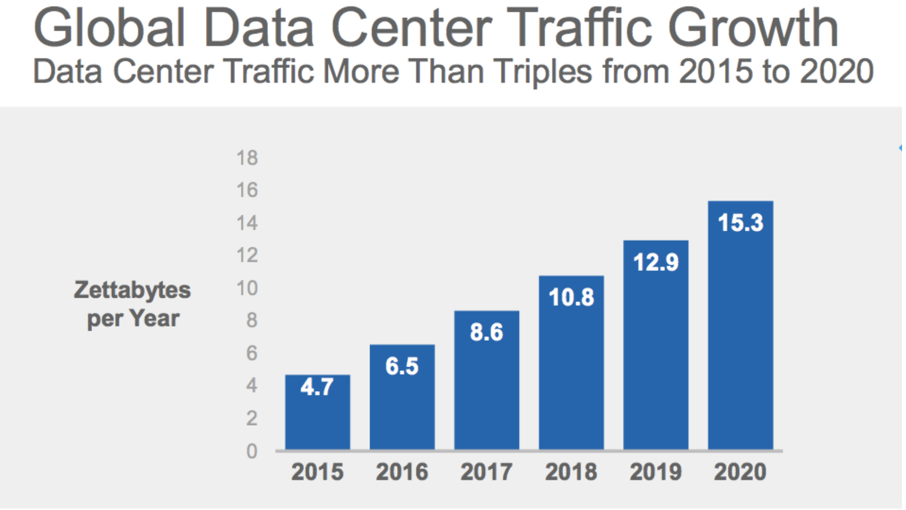
# Information technology: a growing problem



Source: Cisco

>6B hours of video uploaded every month

For every 400 smart phones – 1 server

For every 25 medical wearable devices – 1 server[1]

More datacentres required (and also higher capacity optical fibres for longer distances)

- Google increased number of servers from 25,000 to 2,500,000 in the last 18 years[2]

Photos: Facebook datacentre

Datacentres are used for telecommunication: application hosting, data processing, routing and storage; 75% of the data traffic is inside the data centres[1]

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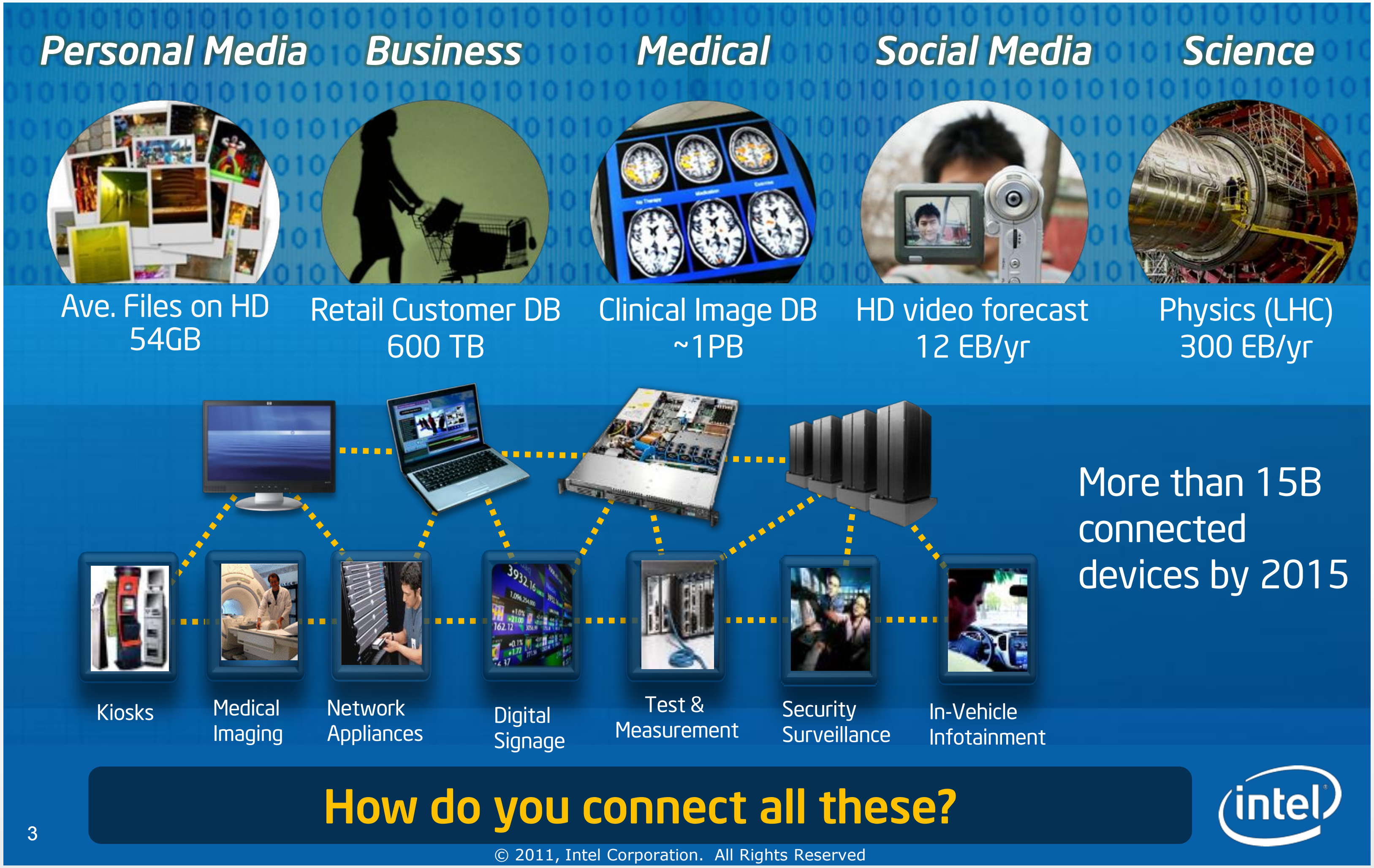
[1] Mario Paniccia, Photonics West, February 2015

[2] https://www.gartner.com



**Personal Media**
Ave. Files on HD
54GB

**Business**
Retail Customer DB
600 TB

**Medical**
Clinical Image DB
~1PB

**Social Media**
HD video forecast
12 EB/yr

**Science**
Physics (LHC)
300 EB/yr

More than 15B connected devices by 2015

**How do you connect all these?**

3

# Mentimeter

- Mentimeter app
- www.mentimeter.com

# Datacentres: huge energy and environmental costs

Datacentres require a huge amount of energy

- Datacentres use ~3% of global electricity
- Citadel (USA, Nevada): 670,000 $m^2$ (130 football pitches), 650 MW; Kolos (Norway, Arctic Circle): 600,000 $m^2$, 1000 MW of computing power
- Electricity is expensive – the lifetime cost of datacentres is now dominated by the cost of electricity (Tianhe 2: no. 1 supercomputer in the world; 3.1M Intel cores, 1.4PB of memory, 125 cabinets; consumes 17.8MW; $1M/year for 1MW; 30% of the cost is in cabling (I/O) and rises)
- Detacentres contributes by 2% to the global carbon emissions*; ICT sector: 4 % of the global carbon emissions and 8-10% of the European energy consumption [1]

**as much as than the entire airline industry!*

The growth of datacentres is not sustainable

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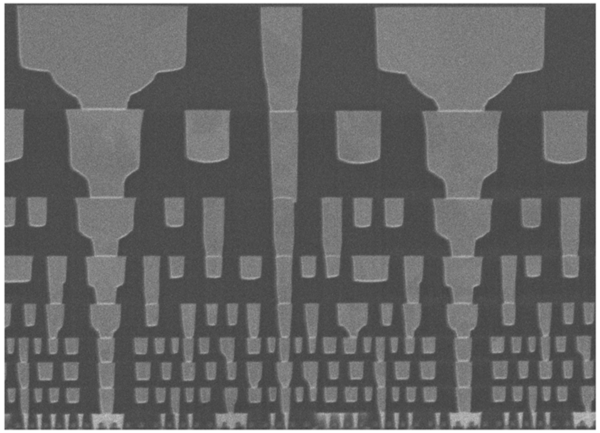
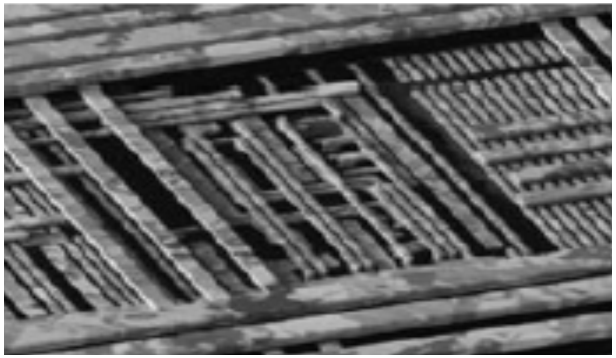
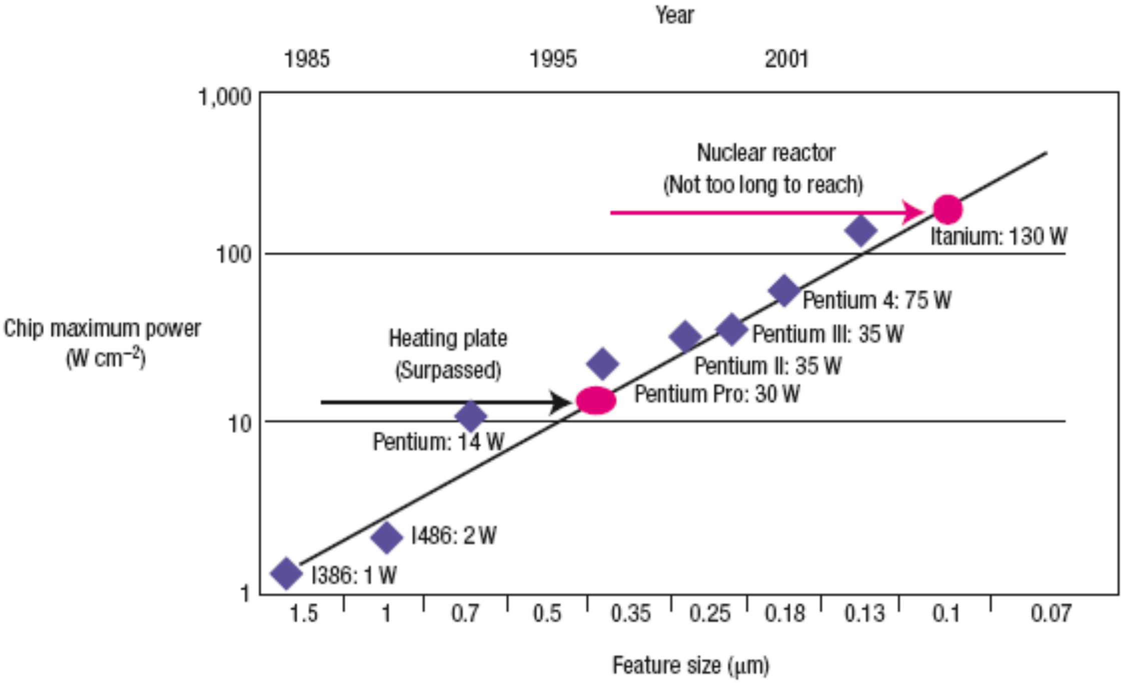
[1] https://ictfootprint.eu

# "Interconnect bottleneck"







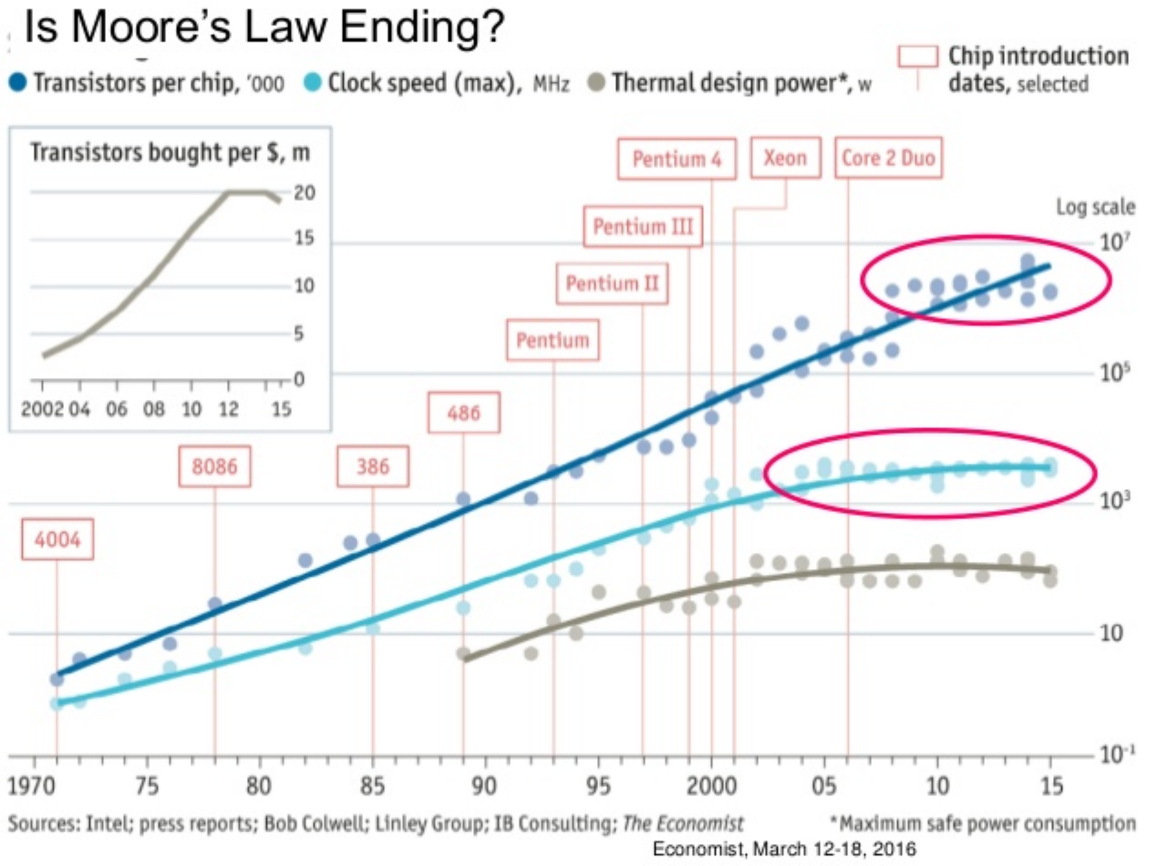
(B. Jalali, *Nature Photonics*, April 2007)

So use optical interconnect!!

# Moore’s law

## Scaling + wafer size + high volume = lower cost

According to Moore’s Law, the number of transistors on a chip doubles every 18 to 24 months.



Sources: Intel; press reports; Bob Colwell; Linley Group; IB Consulting; *The Economist*

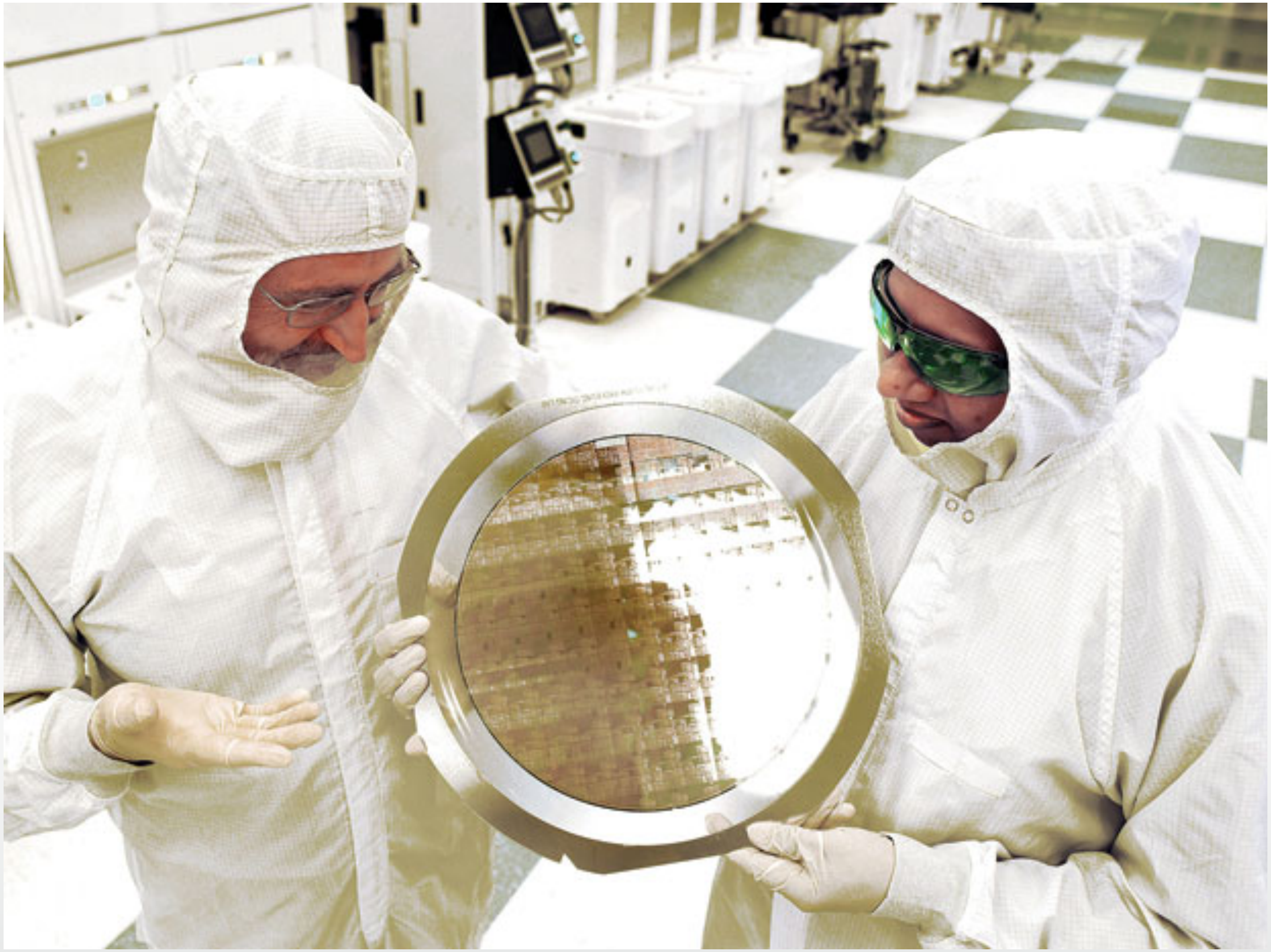
*Maximum safe power consumption

Economist, March 12-18, 2016

# Why Silicon Photonics?

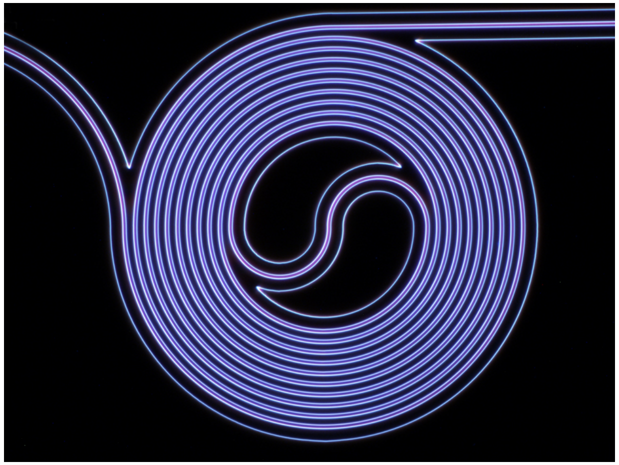
- The prospect of integrating CMOS electronics and photonics on the same substrate:
    - Greater functionality.
    - Improved performance.
    - Cost reductions.
- Mature processing derived from years of development in the electronics industry.
- High refractive index contrast (compact components).
- Lower power interconnects.
- Massive interconnect density (WDM).
- Low cost for mass markets.
- One of the most buoyant photonics fields.
- Many academic and industrial research groups.

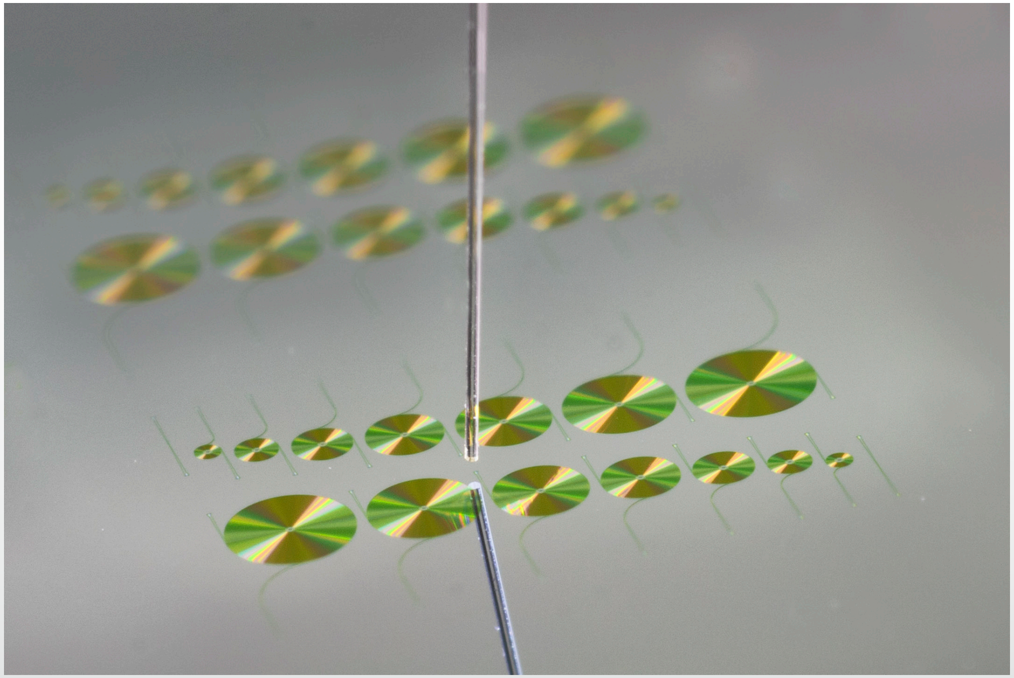
# 18” silicon wafer



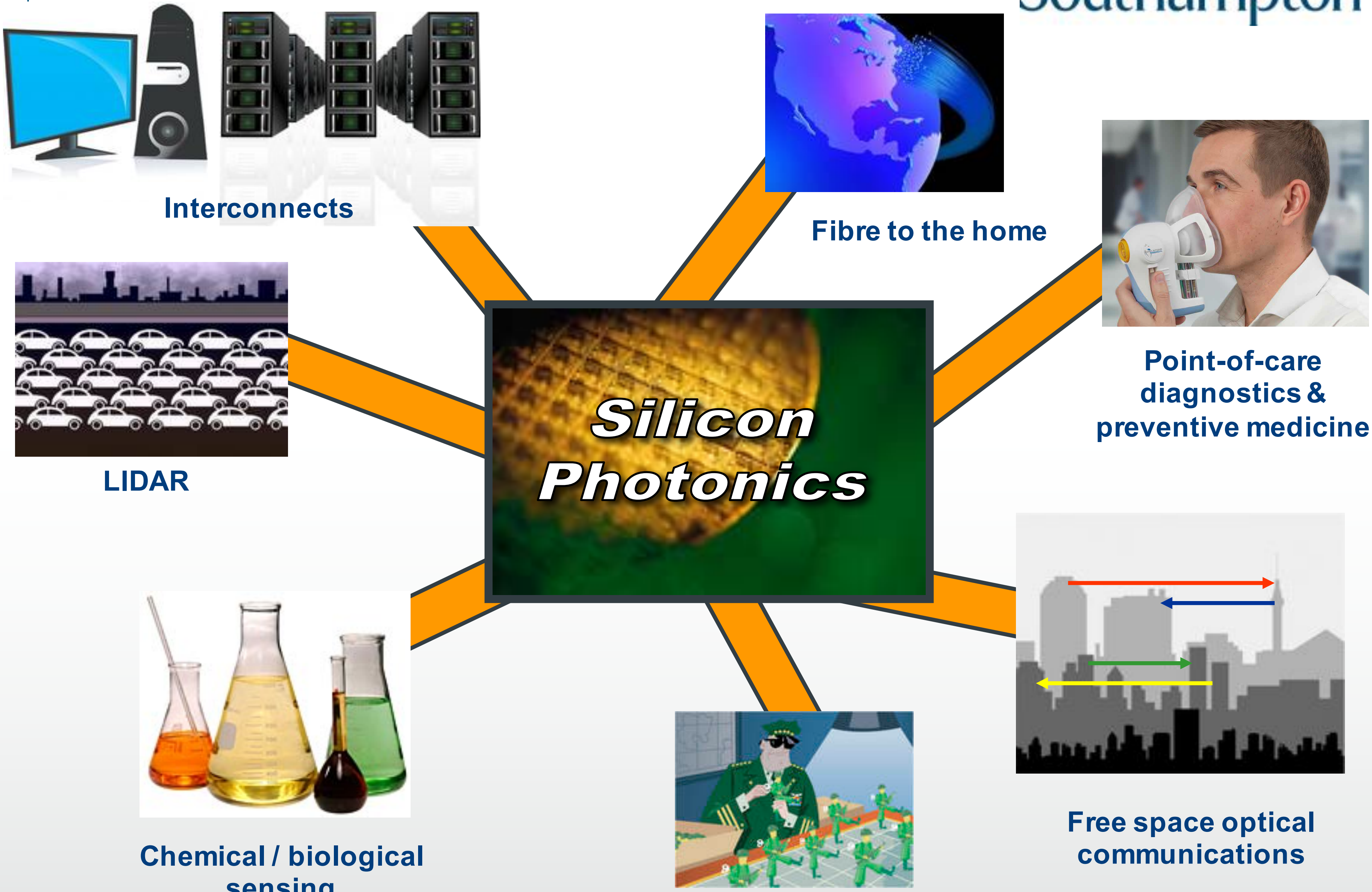
[IEEE Spectrum, September 2016]

# Spiral waveguides: 0.5 m on ~1 mm² area





# Silicon Photonics: Applications



Silicon Photonics

Interconnects

Fibre to the home

Point-of-care diagnostics & preventive medicine

LIDAR

Free space optical communications

Chemical / biological sensing

Military applications

# Silicon Photonics - Companies

ORACLE

SKORPIOS
TECHNOLOGIES

CORNING

HUAWEI

Lightwire

Mellanox
TECHNOLOGIES

CALIOPA
POWERED BY HUAWEI

OCLARO

FiberHome

hp

CISCO

TeraXion

ST
life.augmented

aurrion

molex
one company › a world of innovation

intel

LUXTERA

IBM

Genalyte

Rockley
PHOTONICS

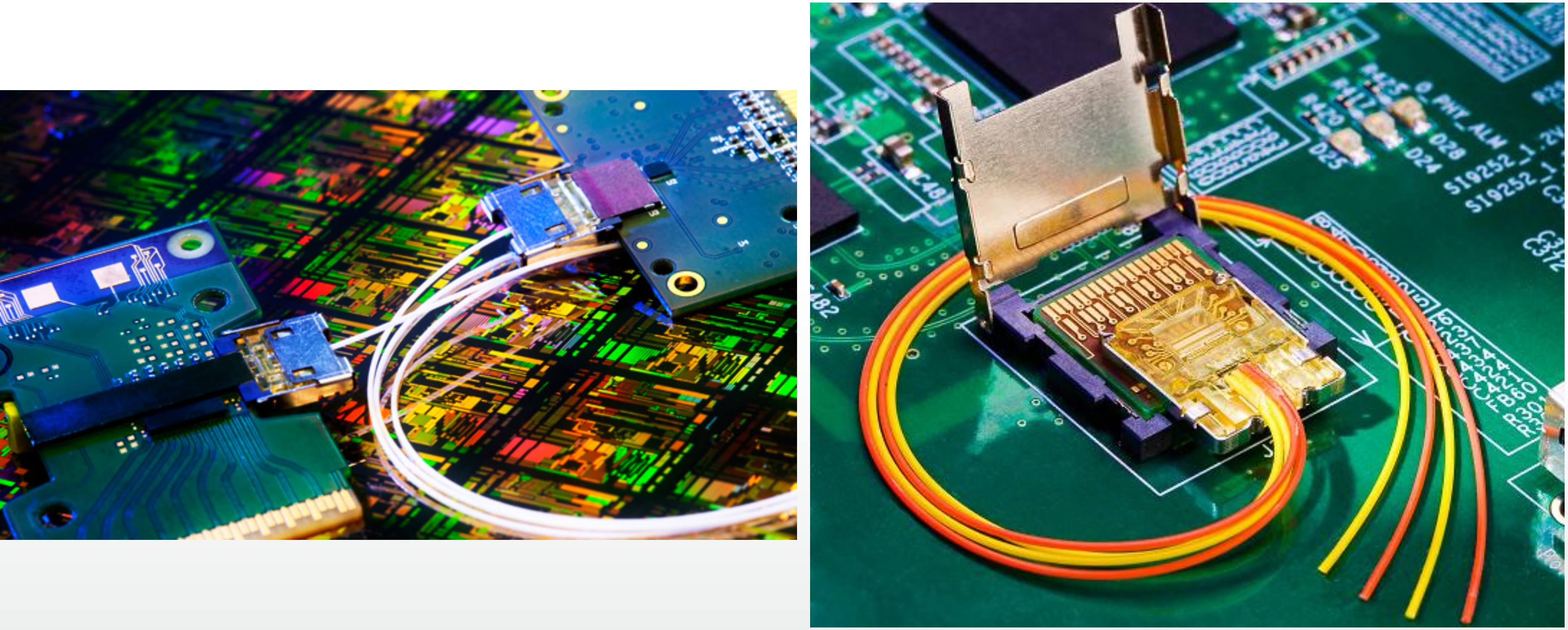
RANOVUS™

FINISAR

ACACIA
COMMUNICATIONS, INC.

*Company list is not exhaustive.*

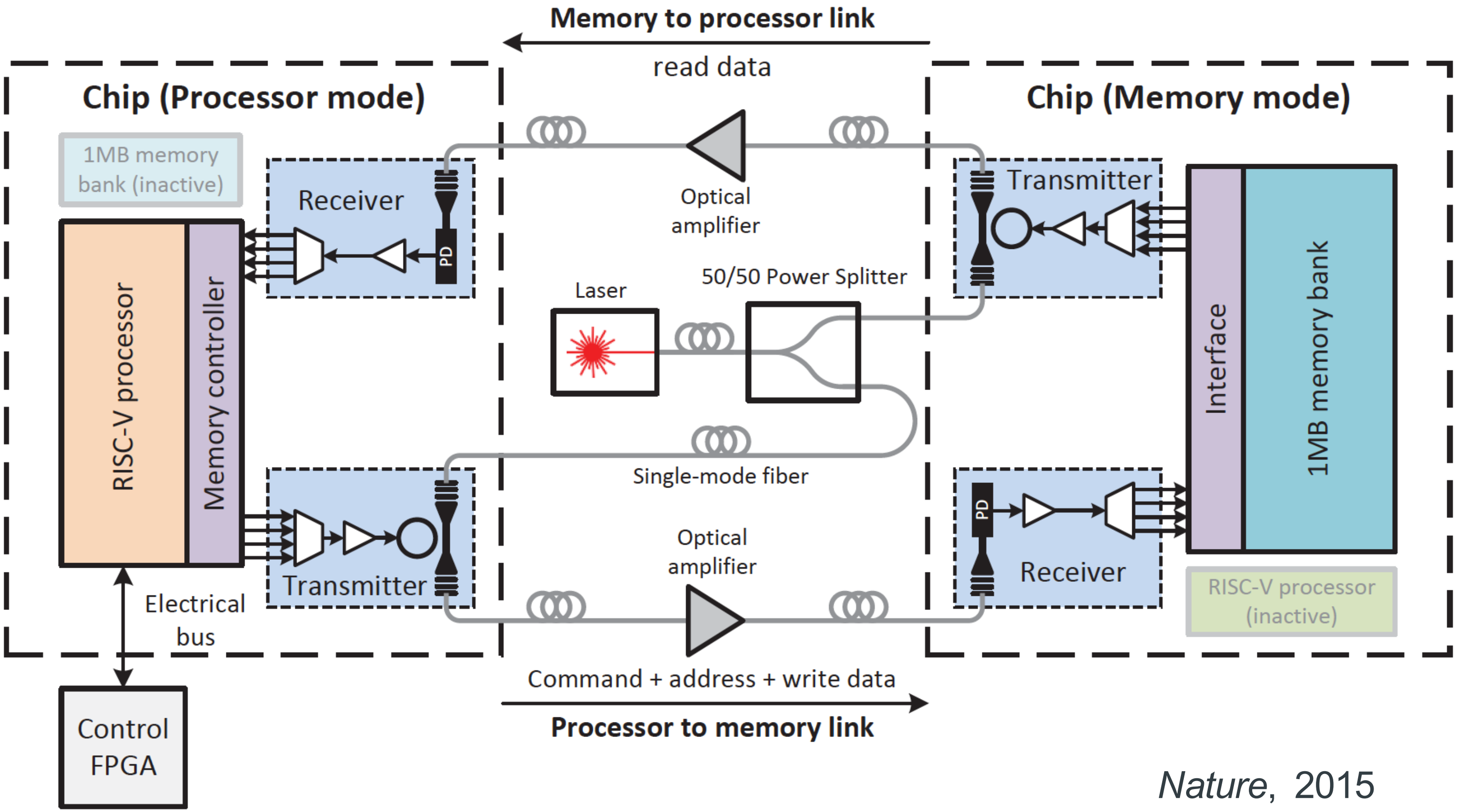
# Active optical cables



*Images: Intel*

# Single-Chip Microprocessor with Integrated Photonic I/O

Chen Sun*[1,2], Mark Wade*[3], Yunsup Lee*[1], Jason Orcutt[2†], Luca Alloatti[2], Michael Georgas[2], Andrew Waterman[1], Jeff Shainline[3‡], Rimas Avizienis[1], Sen Lin[1], Benjamin Moss[2], Rajesh Kumar[3], Fabio Pavanello[3], Amir Atabaki[2], Henry Cook[1], Albert Ou[1], Jonathan Leu[2], Yu-Hsin Chen[2], Krste Asanović[1], Rajeev Ram[2], Miloš Popović[3] & Vladimir Stojanović[1]

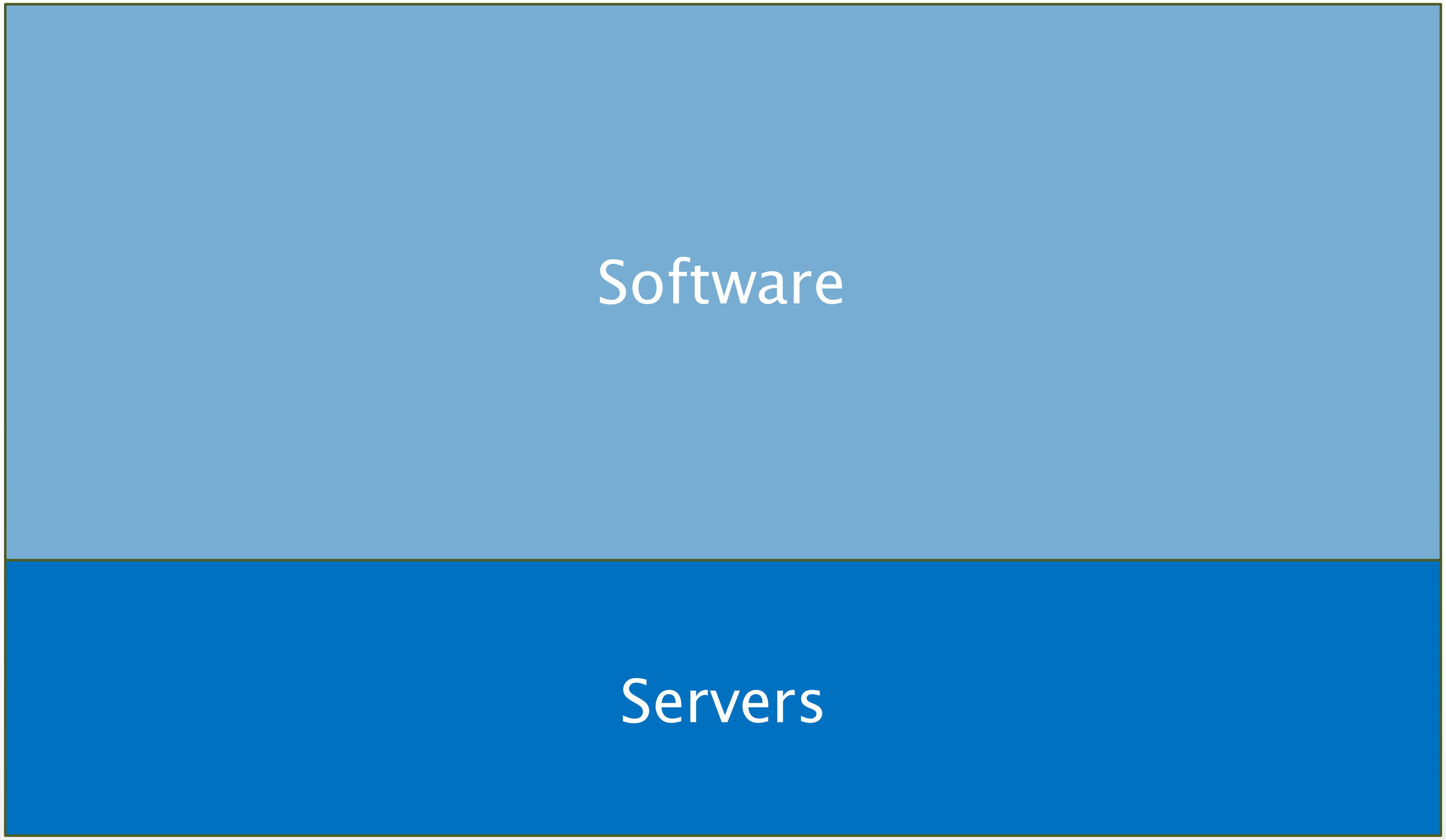


*Nature*, 2015

# Microsoft (5 years ago)

Software

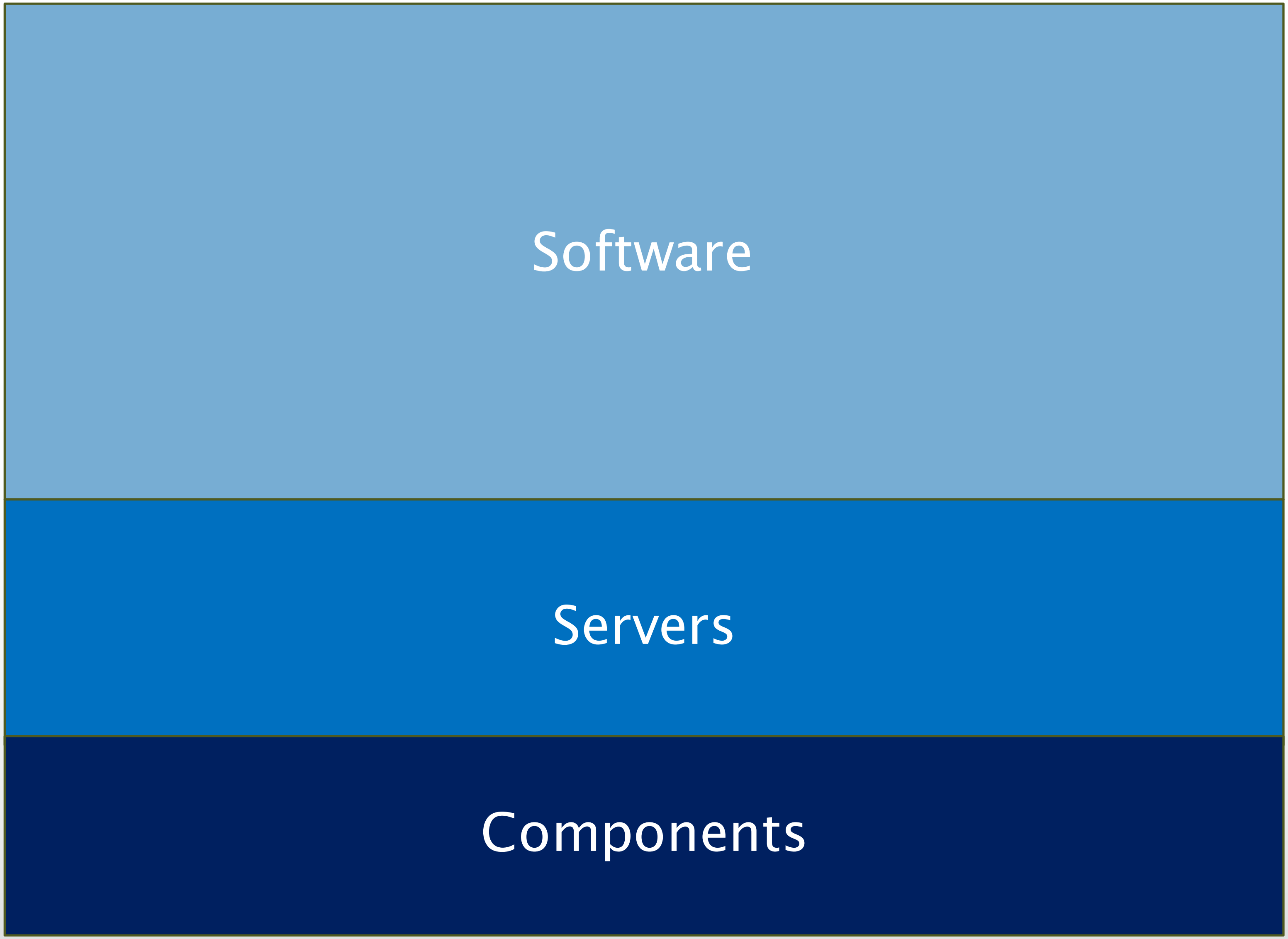
# Microsoft (now)



Software

Servers

# Microsoft (future)

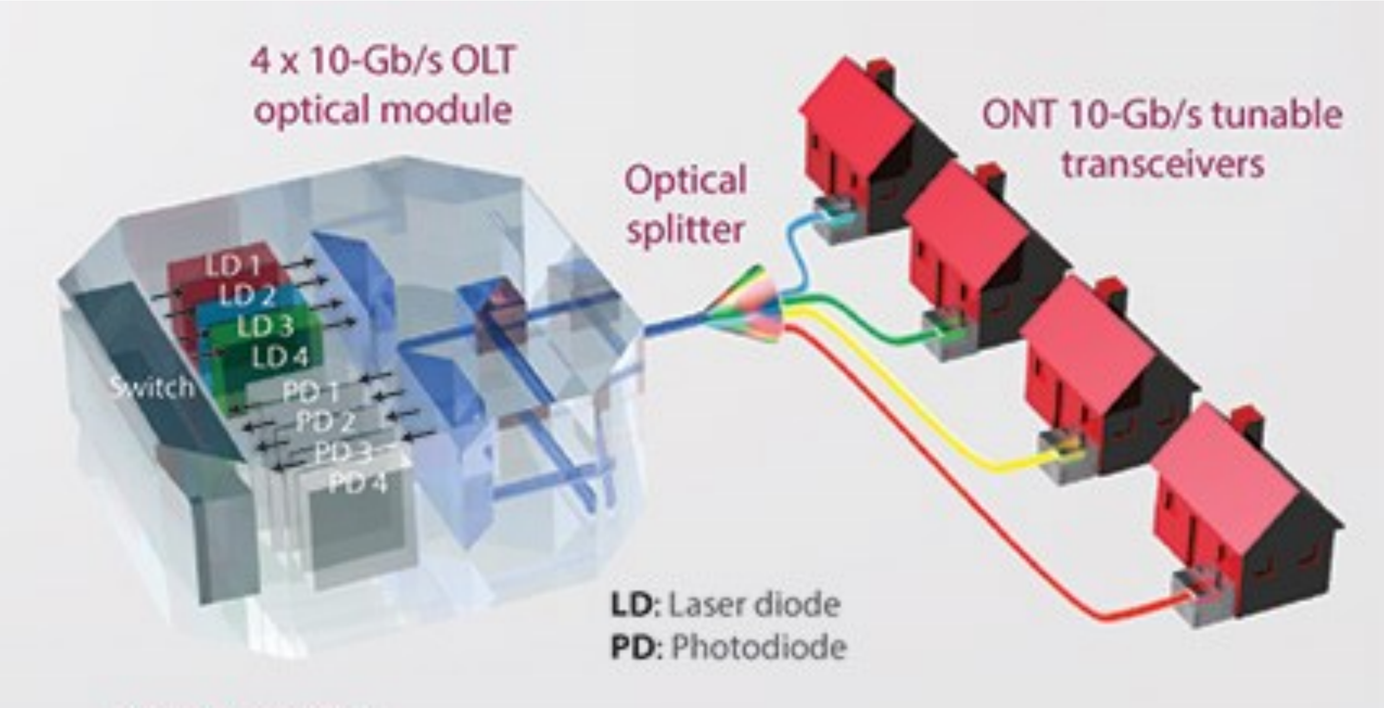


Software

Servers

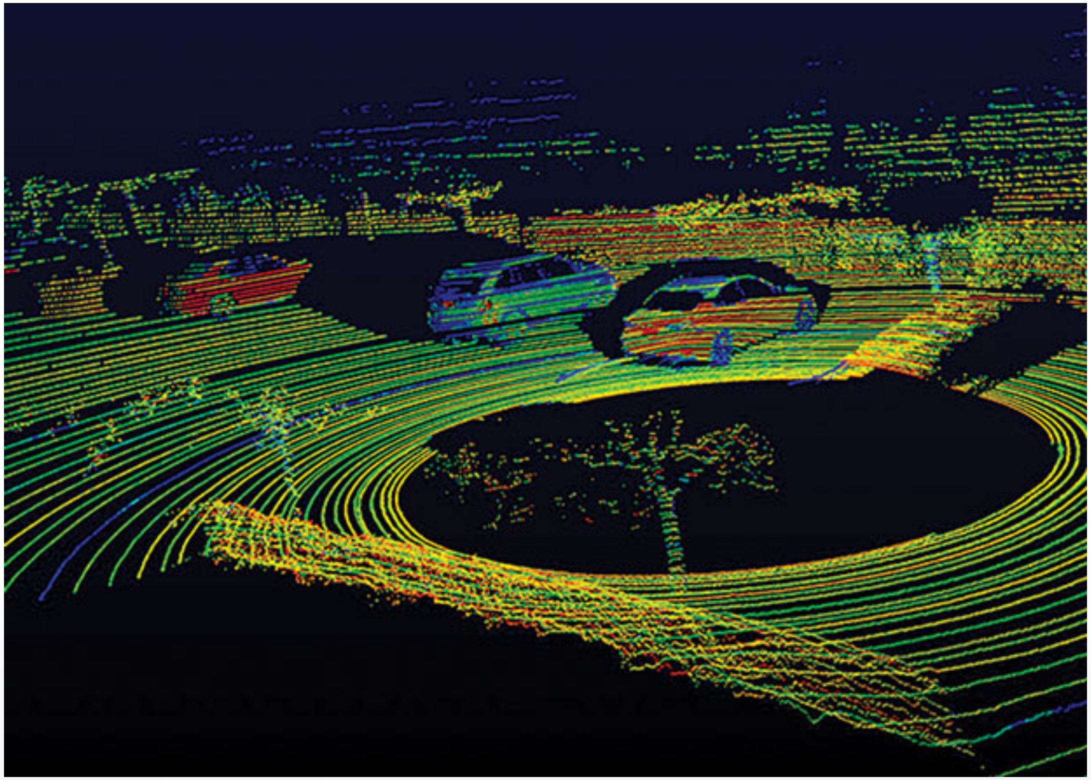
Components

# FTTH: Future network architecture



[Optics & Photonics News, March 2016]

# LIDAR: LIght Detection And Ranging



[IEEE Spectrum, September 2016]

- https://www.youtube.com/watch?v=EBgdskiWIO8
- https://www.youtube.com/watch?v=nXlqv_k4P8Q

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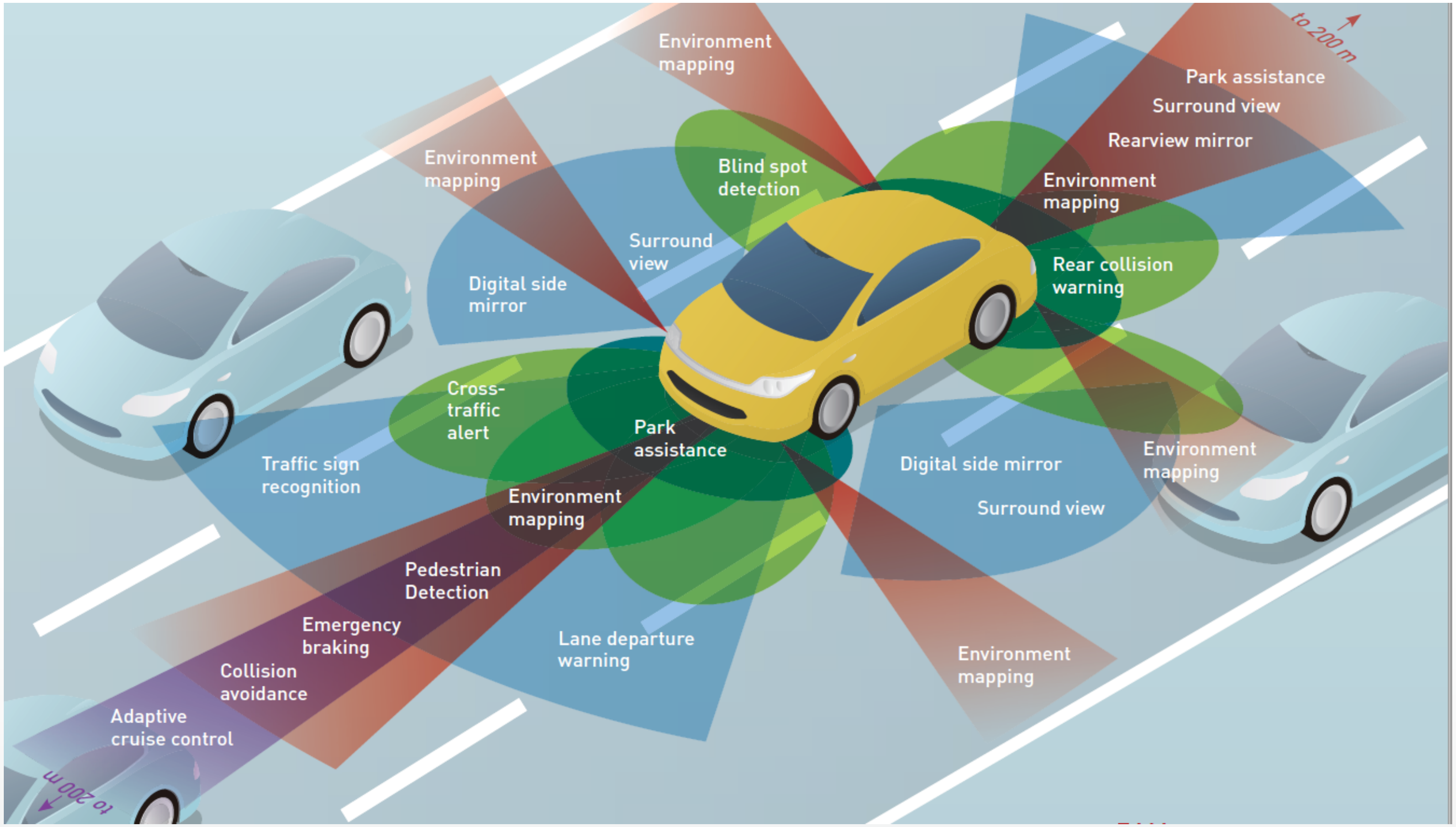
# Car sensors

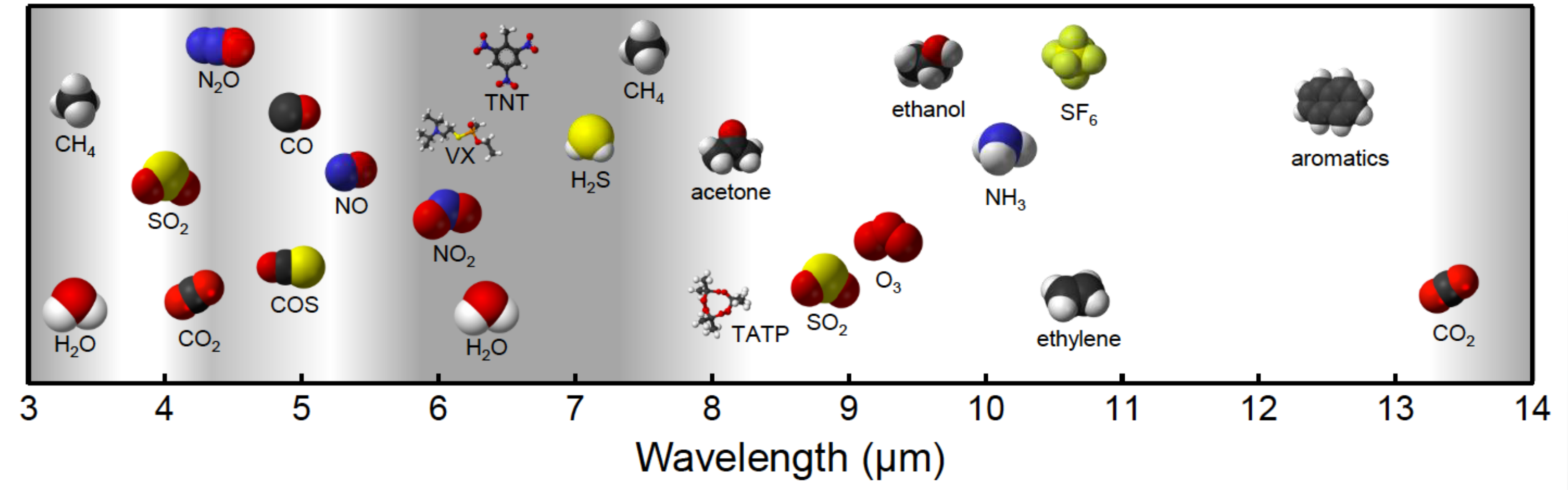
UNIVERSITY OF Southampton



- Long-range radar
- Ultrasound
- Short/medium range radar
- Optical cameras
- Lidar

# Applications of Mid-IR photonics

- Mid-infrared wavelengths are interesting because:
  - Many gases have fundamental vibrations in the 3-14µm wavelength range.
  - Chemical and biological molecules have strong absorption lines in MIR.
  - Atmospheric transmission windows: 3-5µm and 8-14µm.

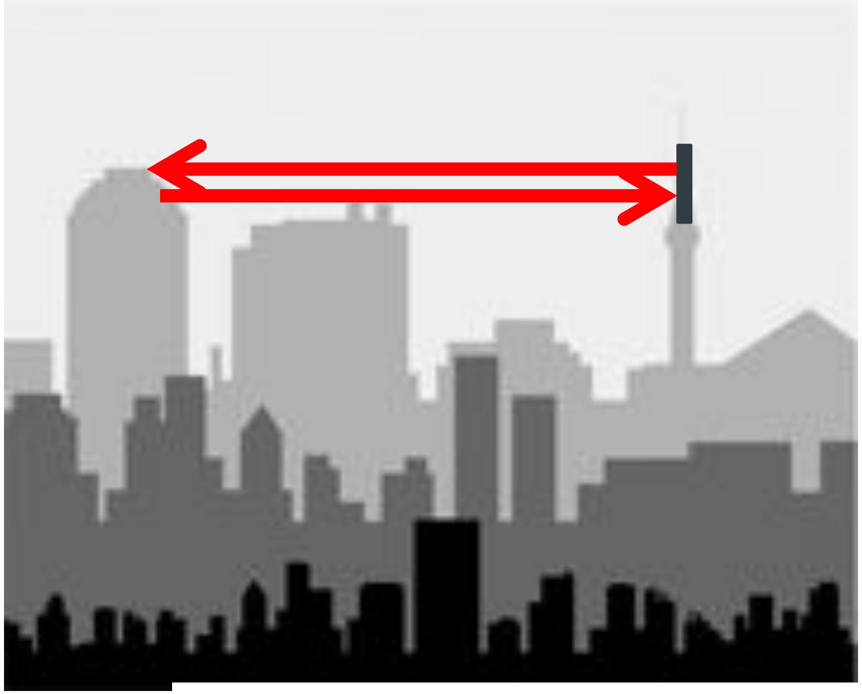


www.daylightsolutions.com

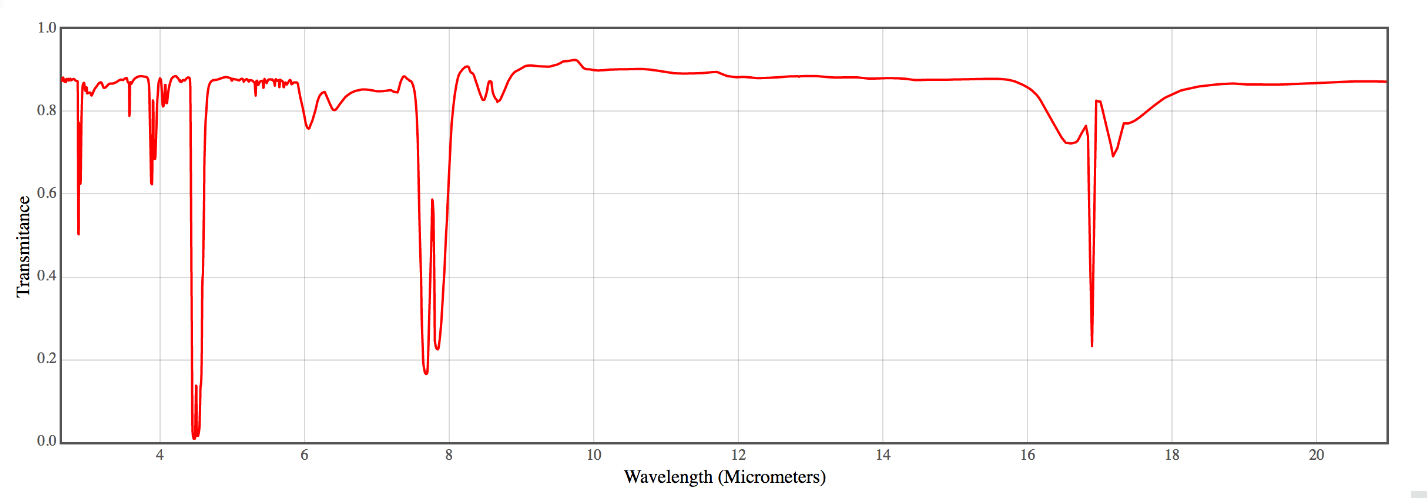
- Possible applications:

  - Trace gas analysis
  - Environmental sensing
  - Medical diagnostics
  - Defense and security
  - Chemical-biological sensing
  - Industrial process control
  - Communications (fibre & free space)
  - Astronomy

# Environmental sensing



- QCL emission
- Long pathways
- Reflection
- Detection of reflected signal
- Detection of gases and their concentrations

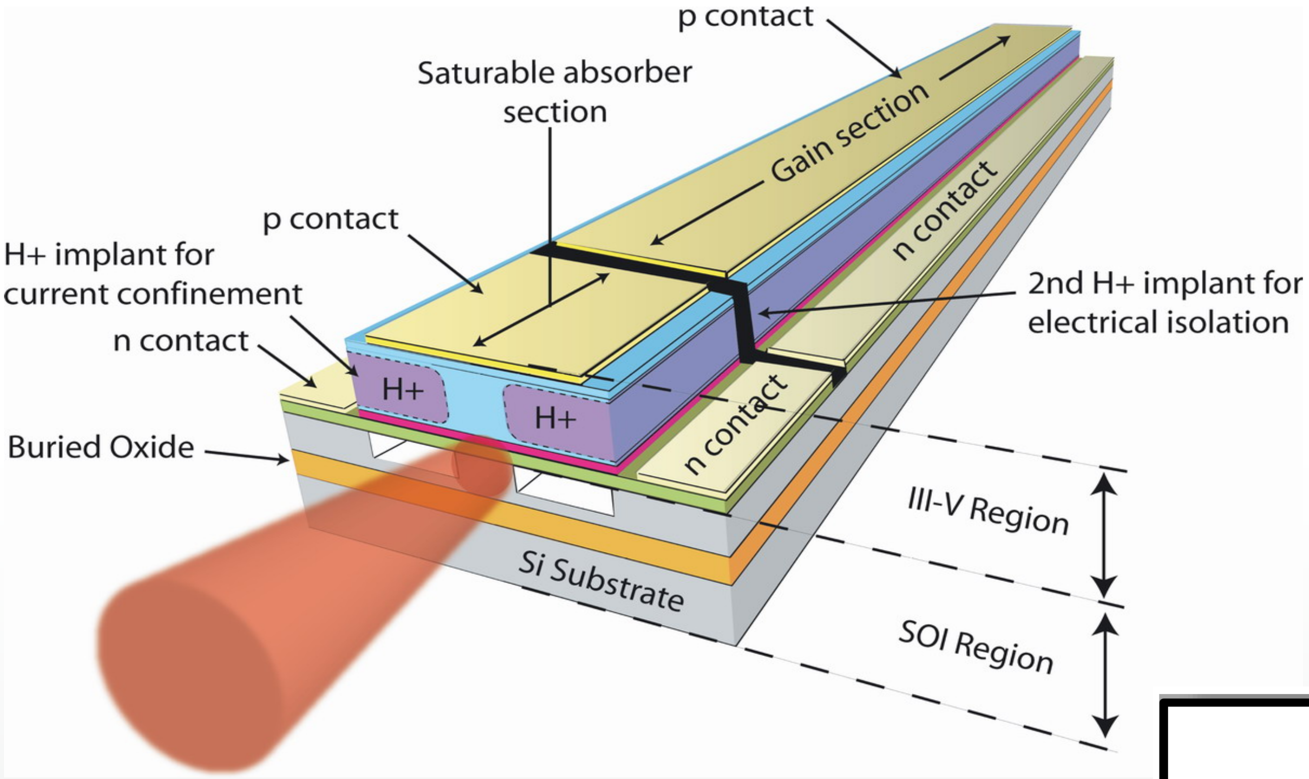


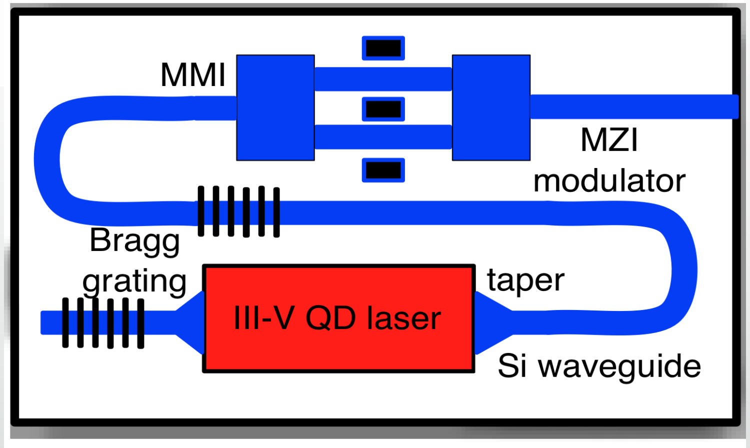
# Sensor - animation

# Are there any drawbacks?

- Indirect bandgap – No light emision

# Hybrid III-V/Si laser



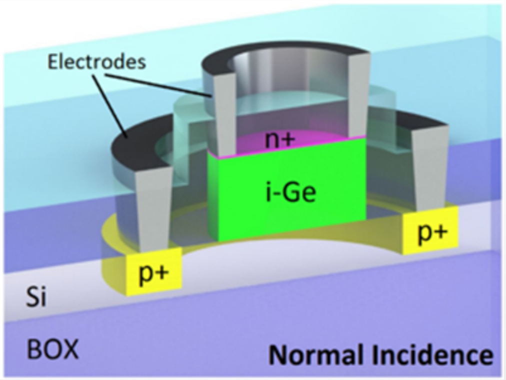


# Are there any drawbacks?

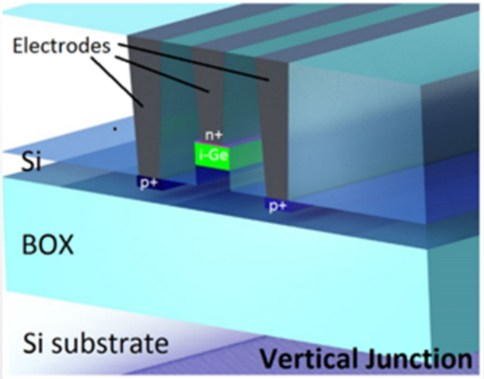
- Indirect bandgap – No light emision
- Transparent @ telecoms wavelengths – No detection in Si → so what can we use?

# Ge detectors

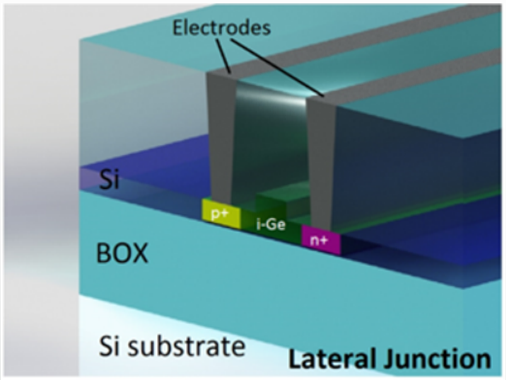
- Normal incidence for direct fibre coupling:
  - Responsivity is a function of Ge layer thickness.
- Waveguide coupled devices can have a *vertical* or *lateral* junction:
  - Vertical junctions can use in-situ doped Ge growth.
  - Lateral junctions can define device width independently of Ge thickness.



Kim et al.: 45 GHz, 0.4 A/W.



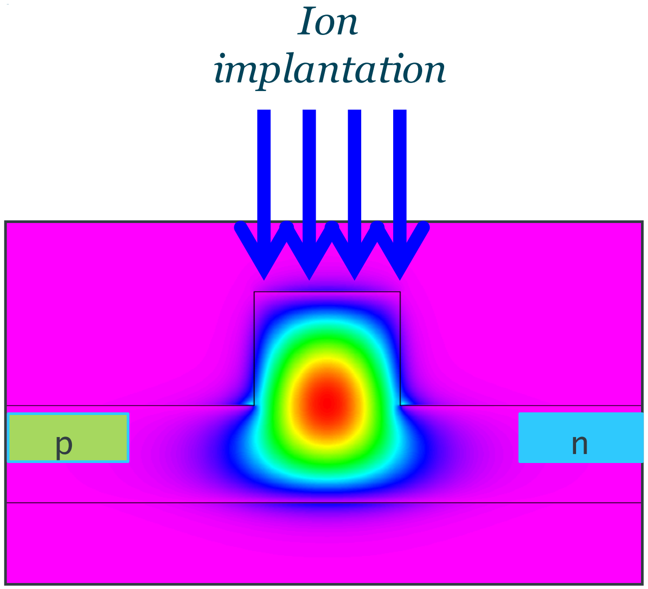
Liao et al.: 36 GHz, 0.95 A/W.

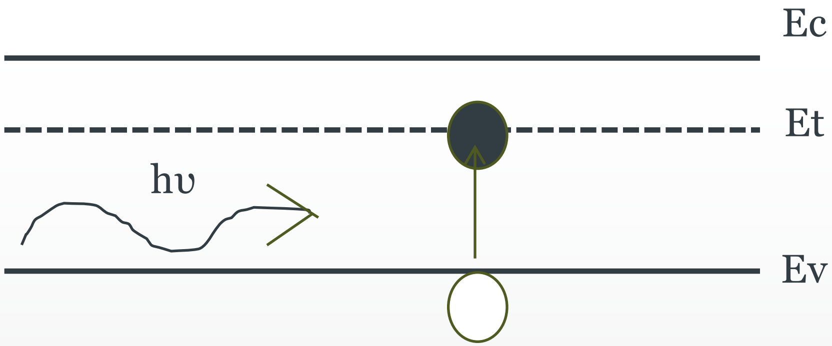


Vivien et al.: 120 GHz, 0.8 A/W.

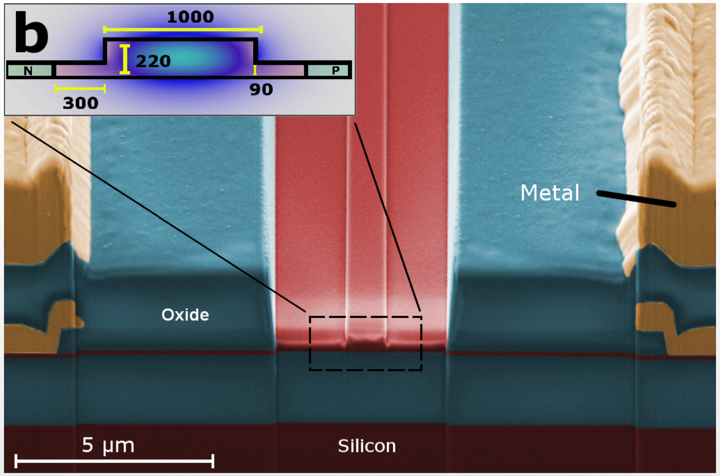
# Si mid-IR detector

- The introduction of defect states by low-dose inert ions, within the bandgap permit the absorption of sub-bandgap photons
- Compatible with standard silicon processing





- Boron implant: 60keV, $10^{13}/cm^2$, introduced through etched oxide window
- Avalanche mode, reverse bias > 20V
- Max speed > 20 Gb/s @ λ~2µm
- R = 0.3 A/W



[J. J. Ackert et al., *Nat. Photon.* **9**, 393 (2015)]

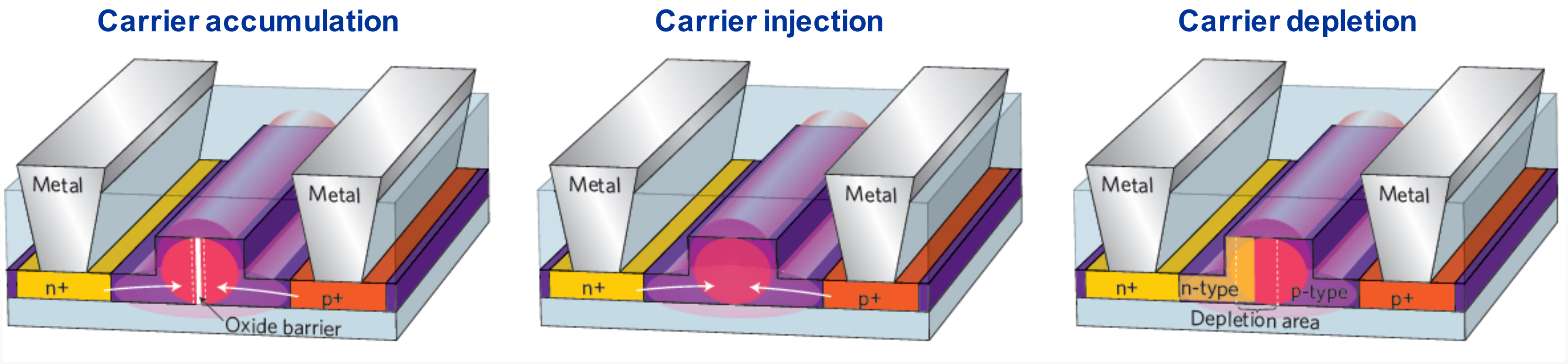
# Are there any drawbacks?

- Indirect bandgap – No light emision
- Transparent @ telecoms wavelengths – No detection
- Centro-symmetric crystal – No Pockels effect for modulation

# Optical modulation in silicon

- Silicon does not exhibit a strong electro-optic effect as used in traditional photonic materials
- Other methods to produce modulation in silicon have therefore been sought:
  - Thermo-optic effect
  - Strain induced Pockels effect
  - Hybridisation (e.g. SiGe, polymers, III-Vs, graphene)
  - Plasma dispersion effect

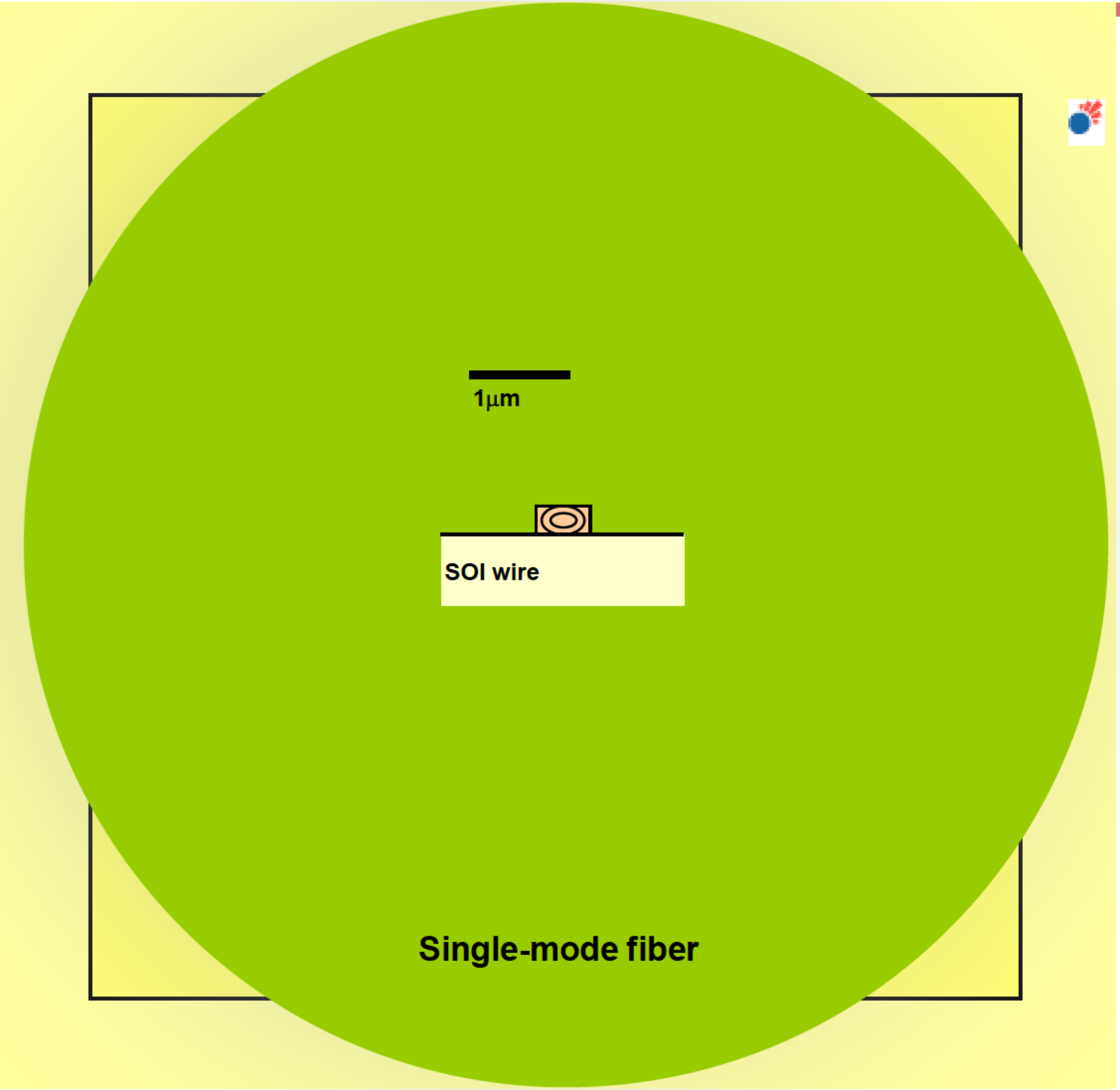
# Modulation in Silicon – animation



[G. T. Reed, G. Z. Mashanovich, F. Y. Gardes, and D. J. Thomson, *Nat. Photon.* **4**, 518 (2010)]

# Are there any drawbacks?

- Indirect bandgap – No light emision
- Transparent @ telecoms wavelengths – No detection
- Centro-symmetric crystal – No Pockels effect for modulation
- Thermo-optic effect can be a problem for temperature stability
- High index contrast – coupling difficult



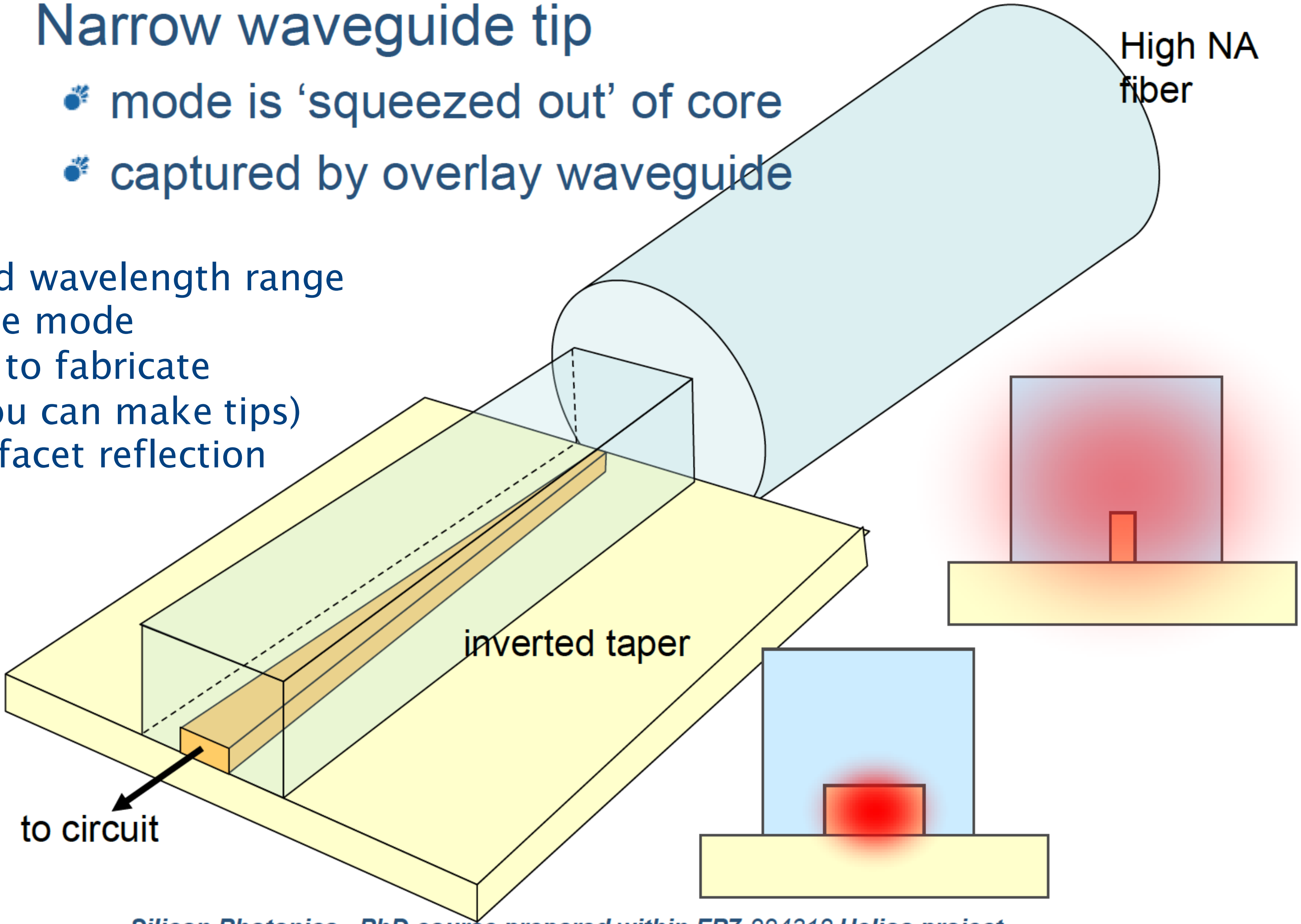
# The problem

- efficient coupling between a submicrometre waveguide and a fiber
- spot-size converter needed :
  - in plane (horizontal)
  - out-of-plane (vertical) : more difficult
- the polarization problem

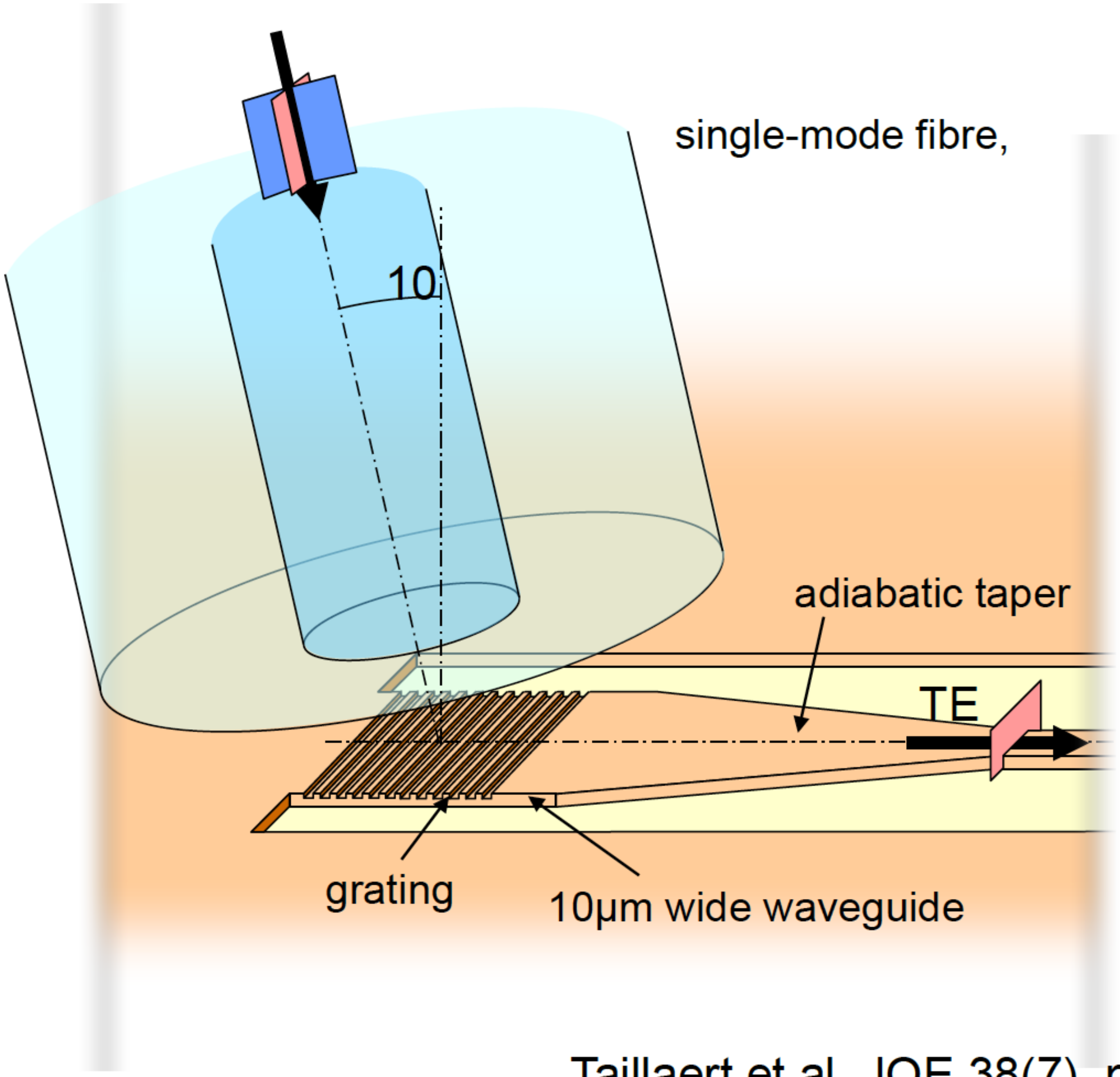
# Tapers: inverted or 3D

- Narrow waveguide tip
  - mode is 'squeezed out' of core
  - captured by overlay waveguide

- Broad wavelength range
- Single mode
- Easy to fabricate (if you can make tips)
- Low facet reflection



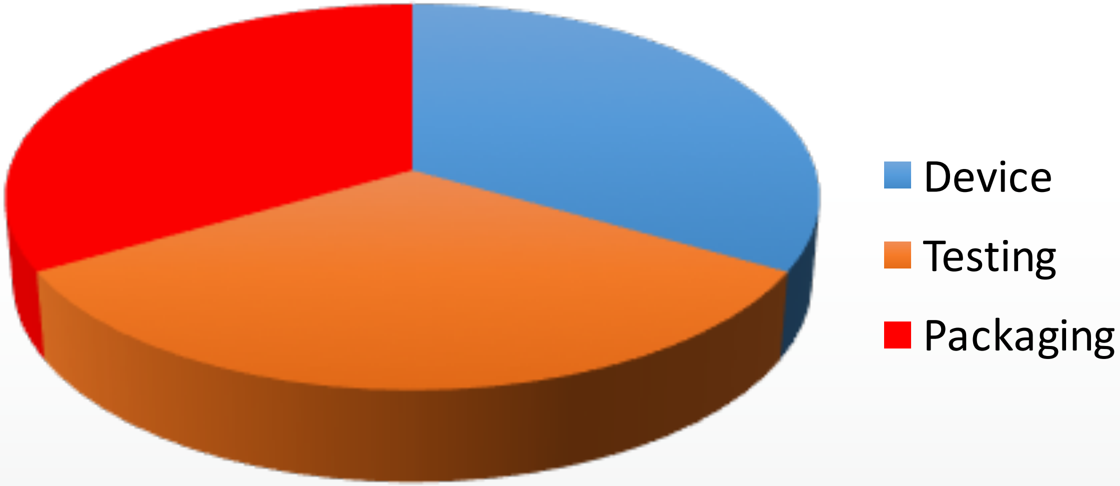
# Grating coupler



- Compatible with SMF-28
- No need for a polished facet
  - Wafer-scale testing
  - Wafer-level packaging
- Flexible and cheap!

Taillaert et al, JQE 38(7), p.949 (2002)

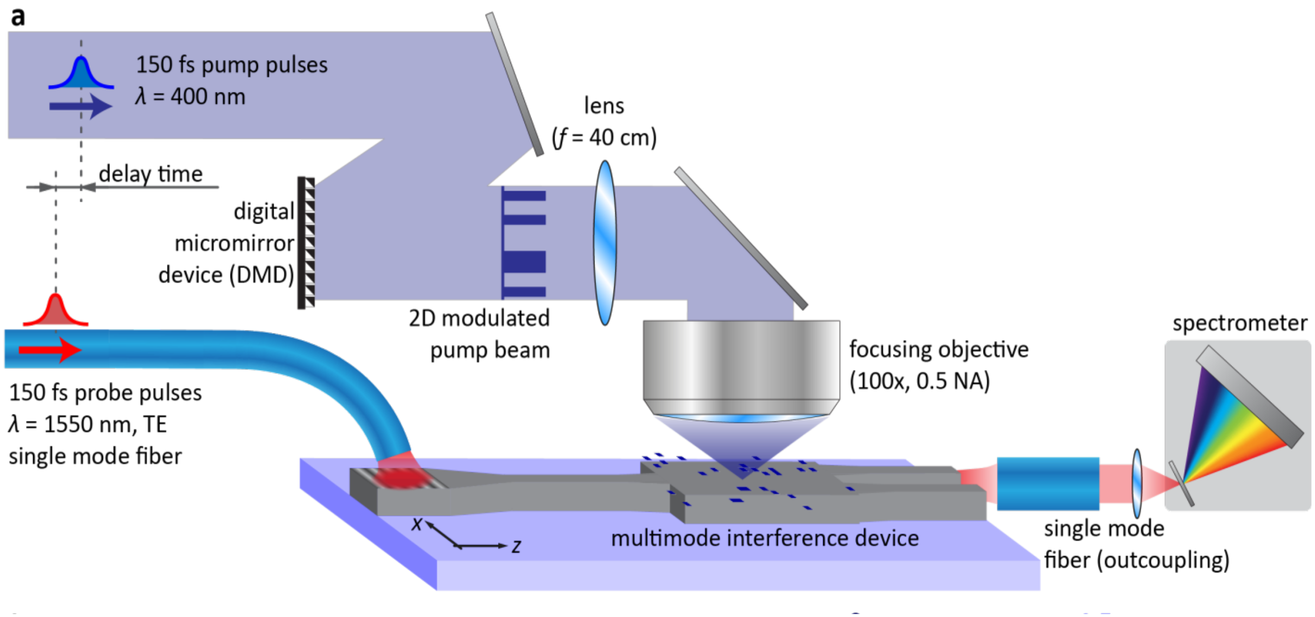
# Testing and packaging

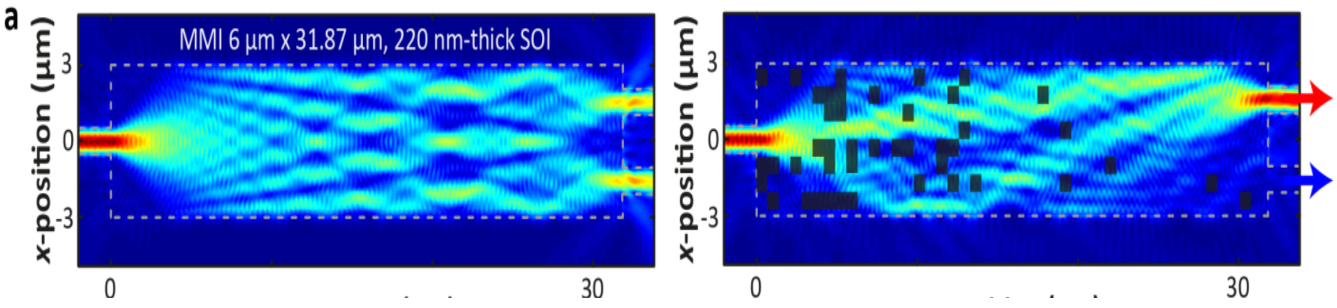


*[H. Rong, PGC, Singapore, 2012]*

# Wafer scale testing animation

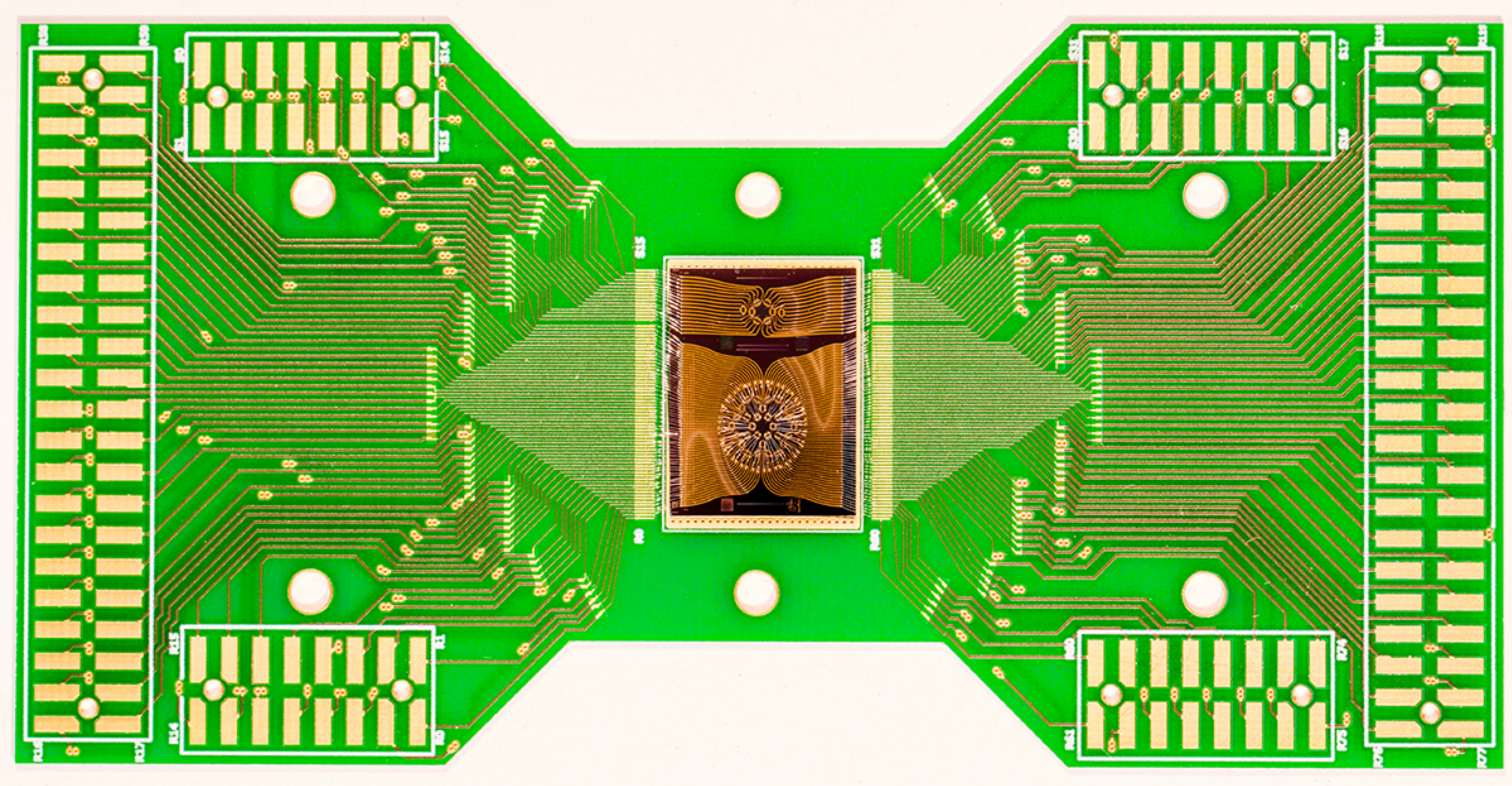
# All-optical spatial light modulator for reconfigurable silicon photonic circuits





[R. Bruck et al., *Optica* **3**, 396 (2016)]

# Photonic programmable circuit – up to 100 different circuits (30 demonstrated)

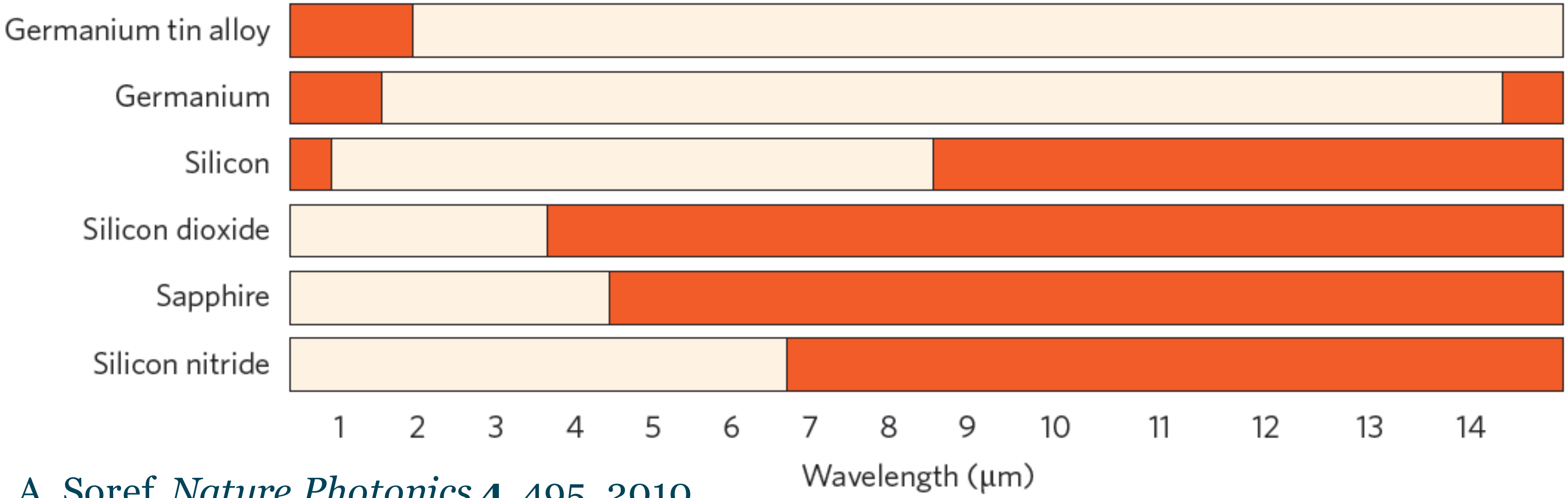


[D. Perez et al., *Nat. Communications* **8**, 636 (2017)]

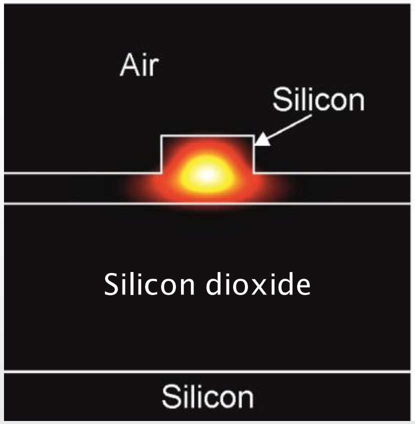
# Collaboration with the University of Malaga

- Photonics devices for the mid-infrared wavelength range
- Potential applications in sensing
  - environmental sensing
  - point-of-care diagnostics in medicine

# Group-IV waveguide platforms

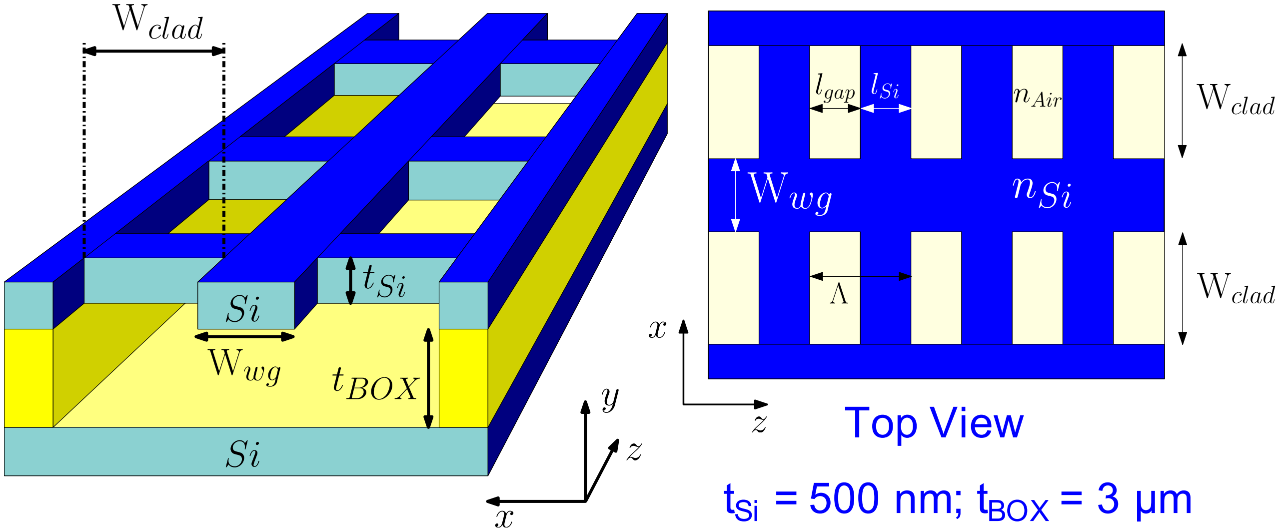


R. A. Soref, *Nature Photonics* **4**, 495, 2010



SOI

# Suspended Si waveguides



Top View

$t_{Si}$ = 500 nm; $t_{BOX}$ = 3 µm

| Parameter | Value |
|---|---|
| $l_{gap}$ (nm) | 450 |
| $l_{Si}$ (nm) | 100 |
| $W_{wg}$ (µm) | 1.3 |
| $W_{clad}$ (µm) | 2.5 |
| $\alpha_{2nd\ mode}$ (dB/cm) | 50 |

## Fabrication constraints

- Subwavelength grating period
- Wider holes ($l_{gap}$) for liquid hydrofluoric (HF) acid etching

## Mechanical Stability

- Smaller $W_{wg}$, smaller $W_{clad}$
- Wider Si supports

## Electromagnetic constraints

- Single-mode and low loss propagation
- Larger $W_{wg}$, larger $W_{clad}$
- Narrower Si supports

Fabrication:

- e-beam lithography
- ICP etching
- HF etching

Characterisation:

- λ=3.8µm

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# Suspended Si fabricated devices

Waveguide loss: 0.8 dB/cm

90 bend loss: 0.014 dB/bend

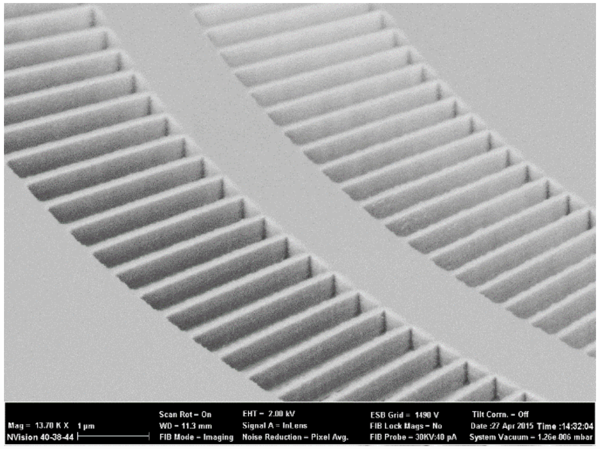
S-bend loss: 0.005 dB/bend

MMI insertion loss <0.5 dB

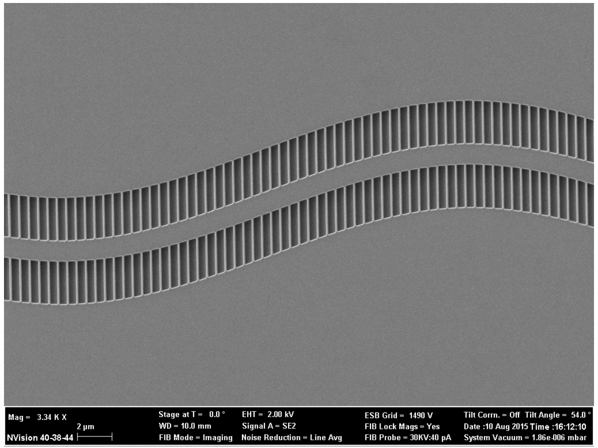
MZI: 1 dB IL

> 15 dB ER

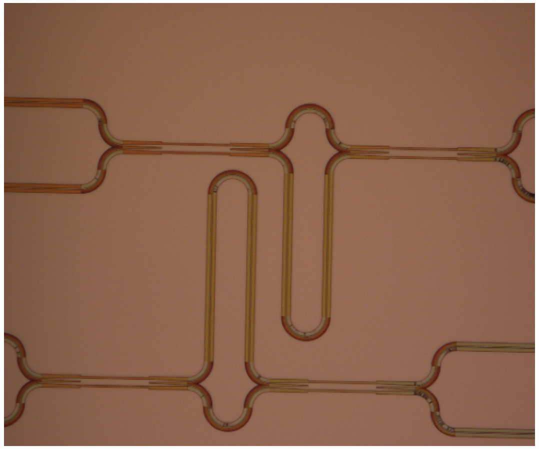
Bends:



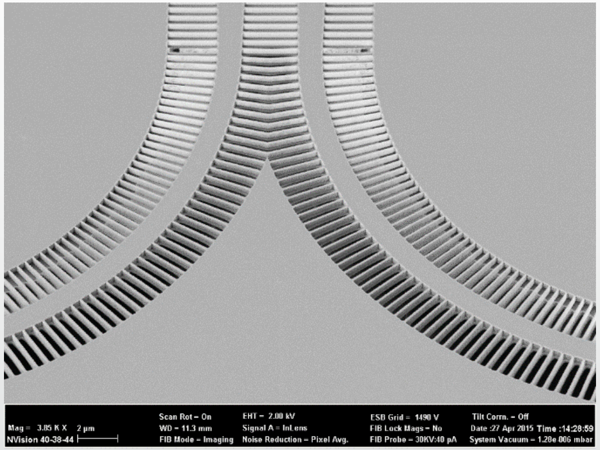
S-Bends:



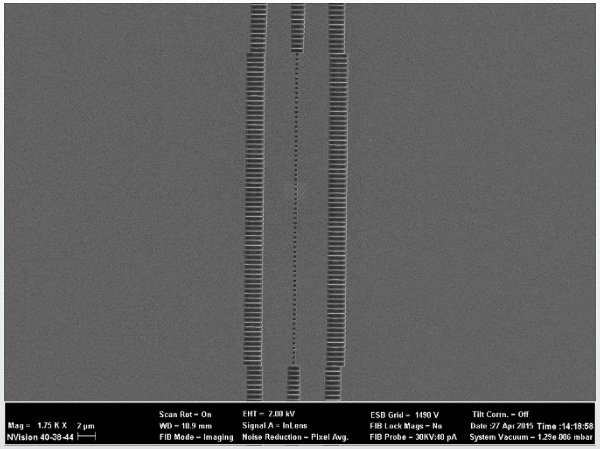
Mach-Zehnders:

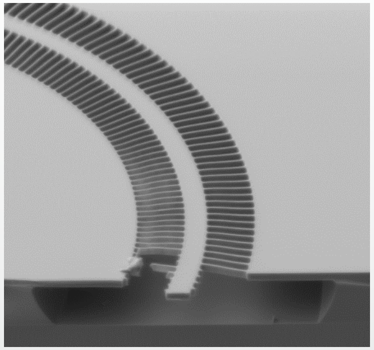


Directional couplers:



Multimode interferometers:





[J. Soler Penades et al. *Opt. Express* 2016]

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# Suspended Si fabricated waveguides at 7.7 μm

1.4 μm Si, 3 μm BOX

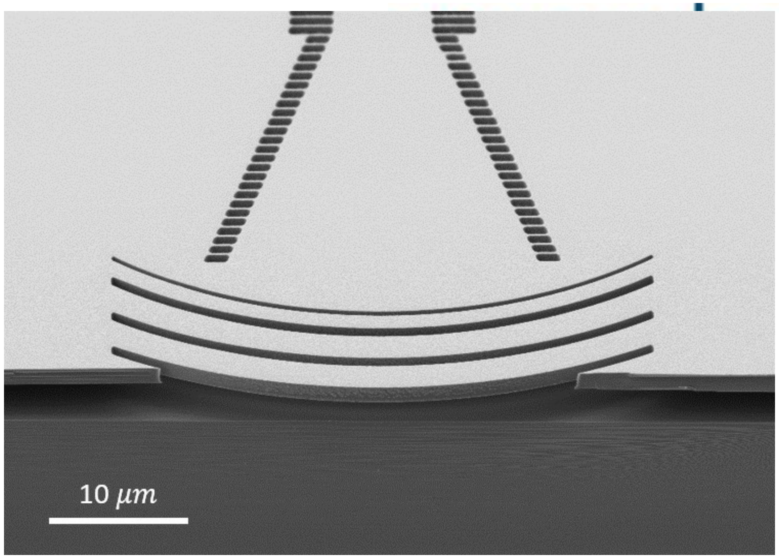
$W_{clad} = 3$ μm, $l_{gap} = 900$ nm, $l_{Si} = 250$ nm

Waveguide loss: 3.1 dB/cm

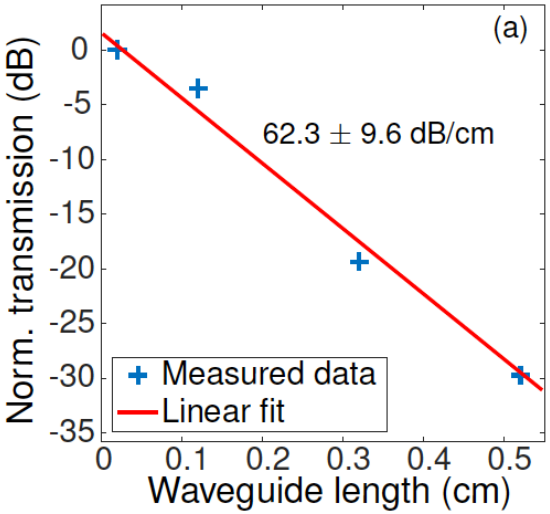
Intrinsic absorption loss = 2.1 dB/cm

S-bend loss: 0.06 dB/bend

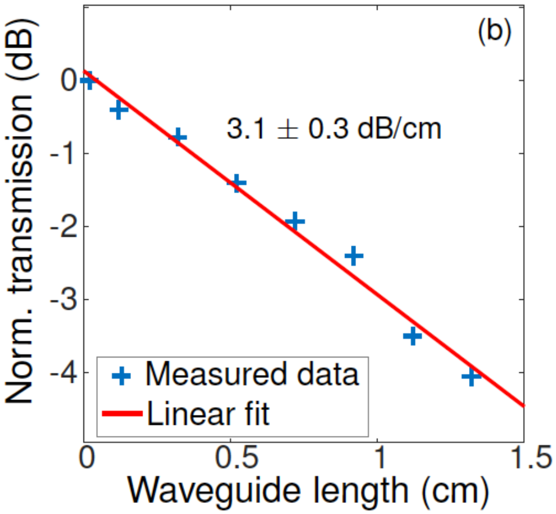
90 bend loss: 0.08 dB/bend



Propagation loss with present BOX



Propagation loss with BOX etched



Current work:
development of a
library of passive Si
suspended devices for
λ ~ 8 μm and Ge
suspended devices for
λ~12 μm

[J. Soler Penades et al., *Opt. Lett.* 2018]

# Final messages

- To students:
  - You study at a great institution, take advantage of that
  - Work with your highly motivated and knowledgeable lecturers
  - Widen your horizons
  - Prepare for future multidisciplinary jobs (demand is high)
  - Fabless companies (design houses)
  - Enjoy!
- To researchers:
  - Our research is becoming more multidisciplinary
  - We need to learn different ‘languages’ and to work in large teams
  - Competition is huge, collaborations are necessary
- To lecturers/departments:
  - We need to change the way we teach (dynamic lectures and syllabuses)
  - We can implement both innovative and research led teaching
  - Both students and lecturers can benefit from this