Karlsruhe Institute of Technology

IPQ

Silicon Photonics, Hybrid Integration, and Frequency Combs: Technologies for High-Bandwidth Communications

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Alfried Krupp von Bohlen und Halbach - Stiftung

KSOP

WaVe phenomena analysis and numerics

PIXAPP Photonic Packaging Pilot Line

erc

TeraSHAPE

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Silicon Photonics, Hybrid Integration, and Frequency Combs: Technologies for High-Bandwidth Communications

Introduction

- Scalability challenges in optical communications
- Silicon photonics and the need for hybrid integration

Silicon-based building blocks for high-bandwidth transceivers

- Waveguides and passive devices
- Photodetectors
- Light sources
- Modulators

Packaging and system assembly

- Coupling interfaces to silicon photonic waveguides
- In-situ waveguide fabrication by 3D laser lithography

Silicon photonic transceivers

- Commercial products and experimental demonstrations
- Towards massively parallel WDM transceivers

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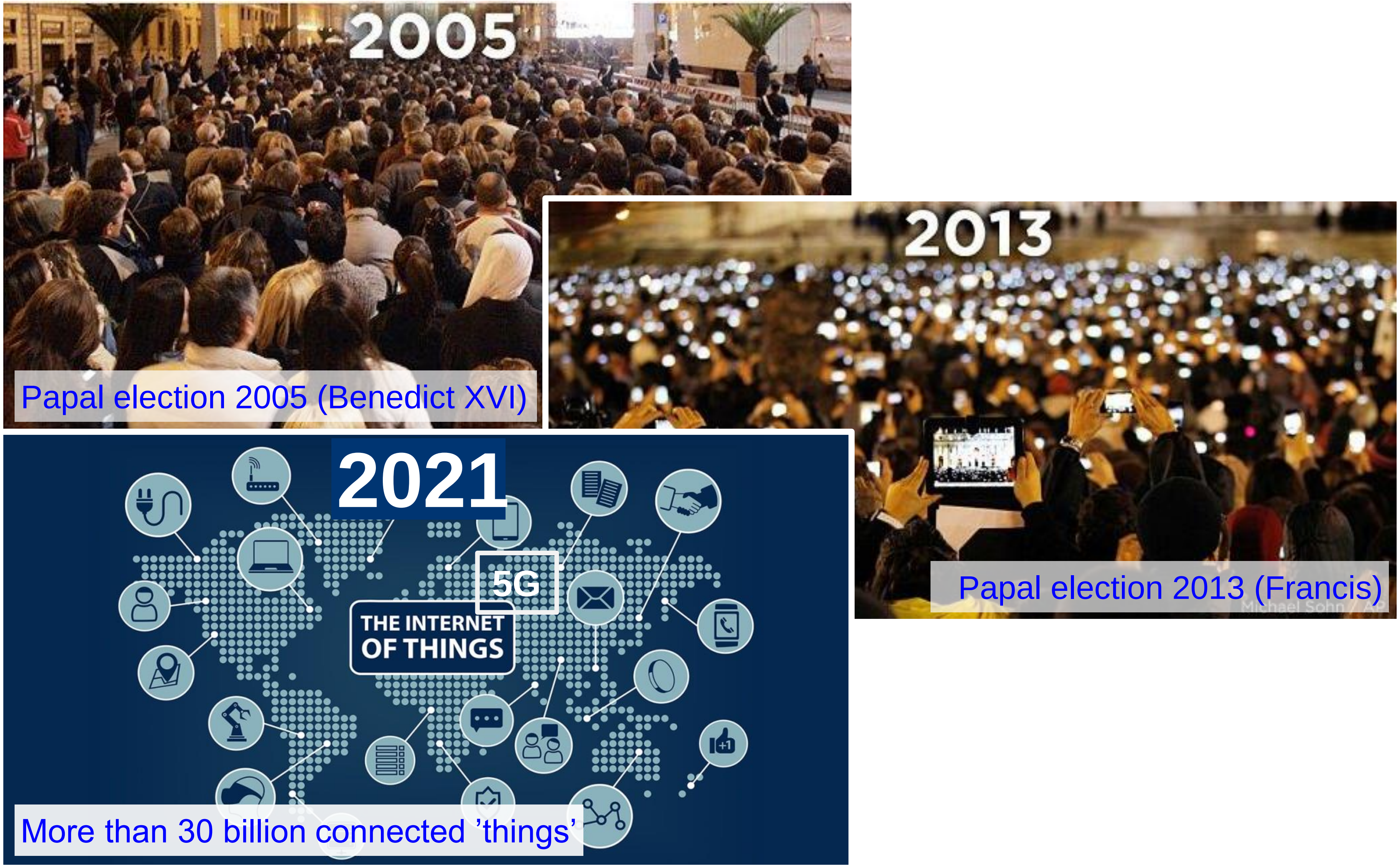
Summary

The need for high-speed communications…



Papal election 2005 (Benedict XVI)

Papal election 2013 (Francis)

More than 30 billion connected 'things'

Picture sources: NBC, IT Pro

Challenge: Communication bandwidth scalability

http://xcentric.com/cloud/datacenter/

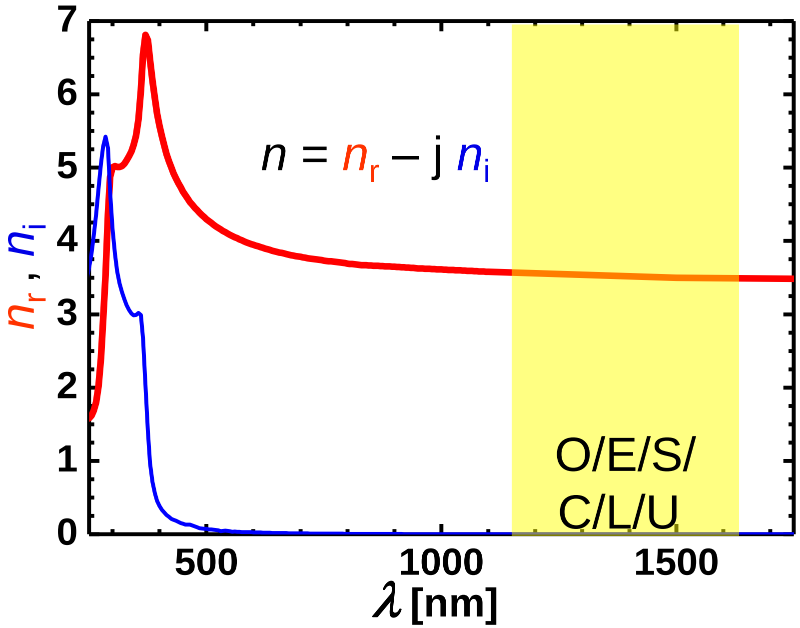
Towards ubiquitous connectivity in data-center, campus-area, and edge networks

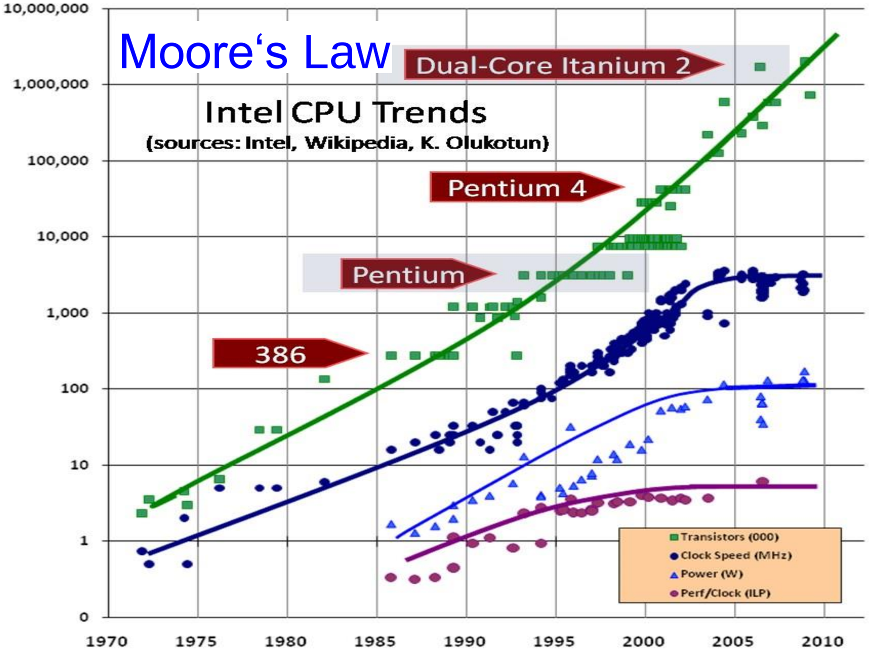
- VCSEL for "short connections"
- Silicon photonics for "longer reach" (> 300 m)
- Massively parallel wavelength division multiplexing (WDM)

Why silicon?

Silicon:

- Transparent at IR telecom wavelengths
- High refractive index
  - ⇒ Nanophotonic devices
    Dense integration
    Small active volumes
    Ultra-fast low-power switching

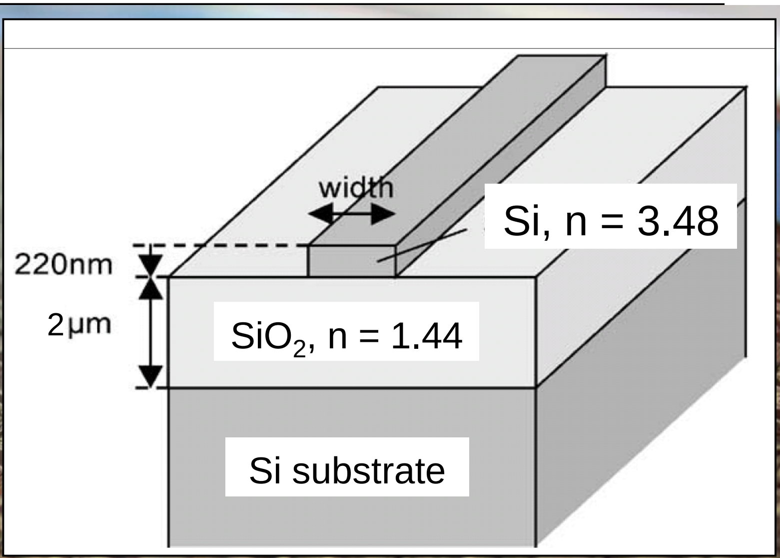


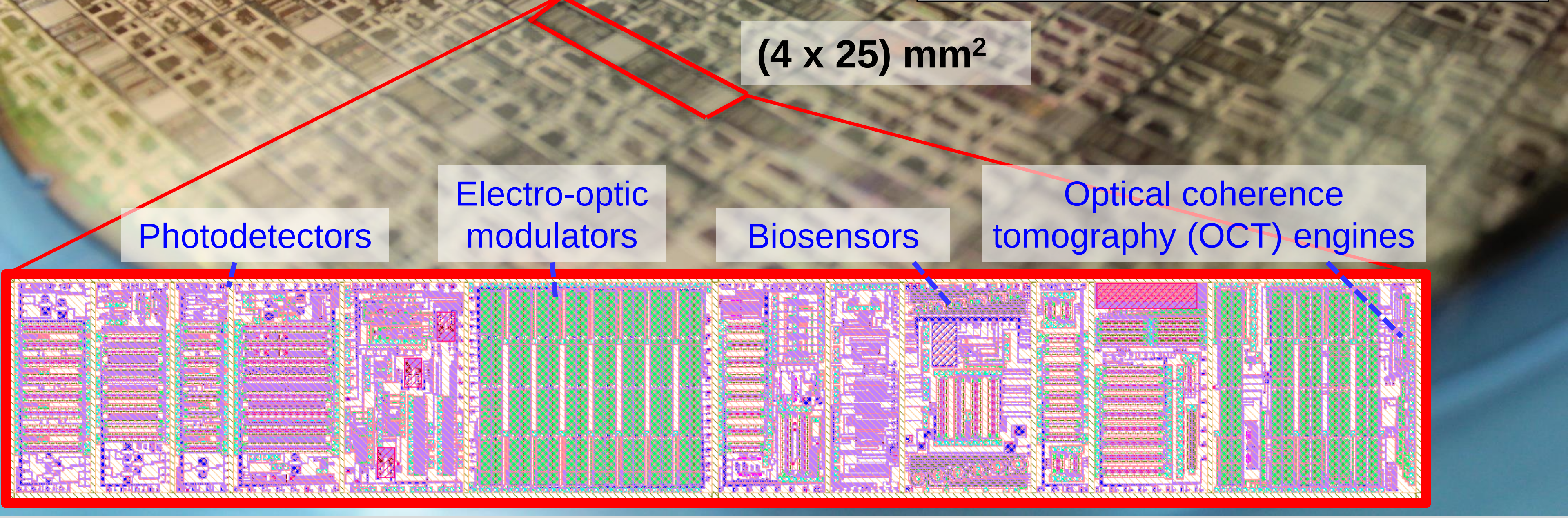


- Availability of sophisticated CMOS fabrication processes
  - ⇒ Low-cost high-yield mass-production
    Joint integration of photonics and electronics

Silicon photonics: Strengths

- High-index-contrast SOI waveguides
  ⇒ High integration density
- Mature CMOS technology
  ⇒ Large-scale photonic-electronic integration with high yield
- Ecosystem of foundries
  ⇒ Fabless fabrication: Share investment and development costs by multi-project-wafer (MPW) runs and process design kits (PDK)




(4 x 25) mm^2

Photodetectors

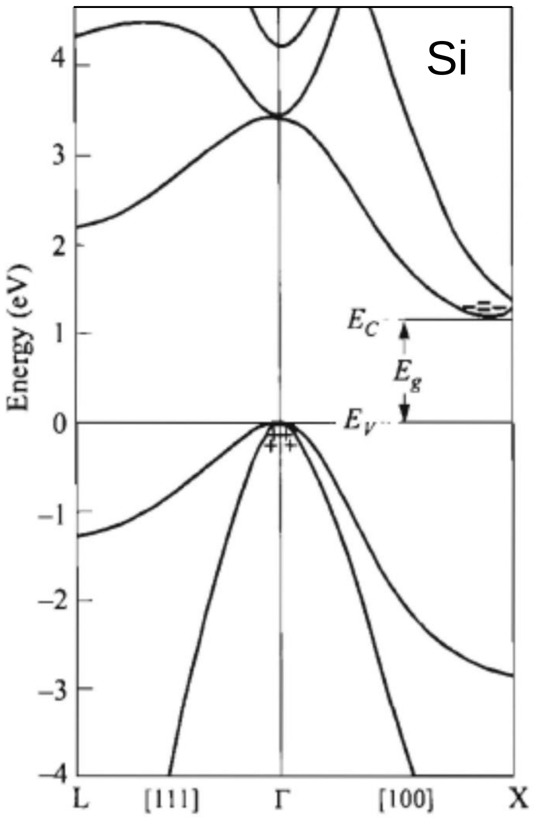
Electro-optic modulators

Biosensors

Optical coherence tomography (OCT) engines

Silicon photonics: Weaknesses

Indirect bandgap inhibits light emission

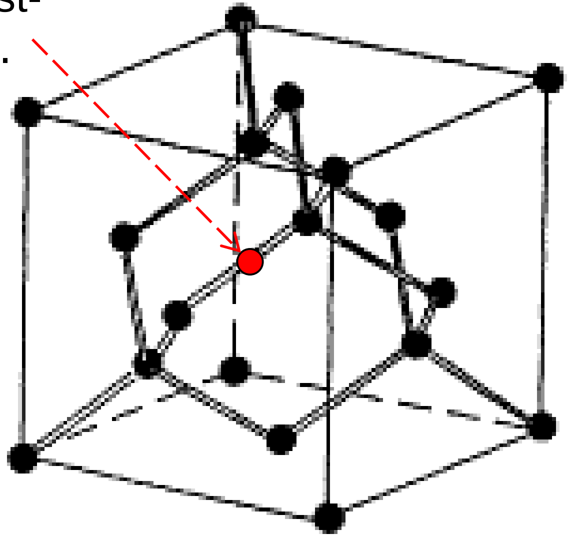


⇒ External lasers of hybrid integration of direct-bandgap III-V materials on silicon

Quelle: Sze, Semiconductor Devices

No Pockels effect due to inversion symmetry of the diamond crystal lattice

Inversion point:
Mid-point of nearest-neighbour bonds.



$$T_{q'q} = -\delta_{q'q}$$

$$\Rightarrow \chi^{(n)}_{q_0:q_1\ldots q_n} = (-1)^{n+1}\chi^{(n)}_{q_0:q_1\ldots q_n}$$
$$= 0 \quad \text{for even} \quad n.$$

⇒ Hybrid integration of electro-optic materials on silicon chips or alternative techniques to modulate the refractive index in silicon

Bierdeckel-Rechnung ("back-of-the envelope" calculation)

SiP TRx market in 2023:

18 million 100 Gbit/s TRx, 5 mm² each
⇒ 90 million mm²
⇒ 3000 pieces of 8" wafers (30 000 mm²

CMOS fab capacity 2018*:

TSMC: 12 million 12" wafers in 11 fabs in 2018
⇒ 120 wafer/h/fab in 2018 (12"!!!)

⇒ Annual SiP Ethernet TRx supply forecasted for 2023 can be produced within 25 h using 2018 equipment of a single fab.

Overall market volumes:

SiP prediction for 2023: (w/o laser integration)	650 million $
Electronic CMOS IC in 2023:	> 400 billion $

⇒ "High-volume" SiP transceivers will not by no means be a "volume business" for CMOS fabs!

*https://www.tsmc.com/english/dedicatedFoundry/manufacturing/fab_capacity.htm

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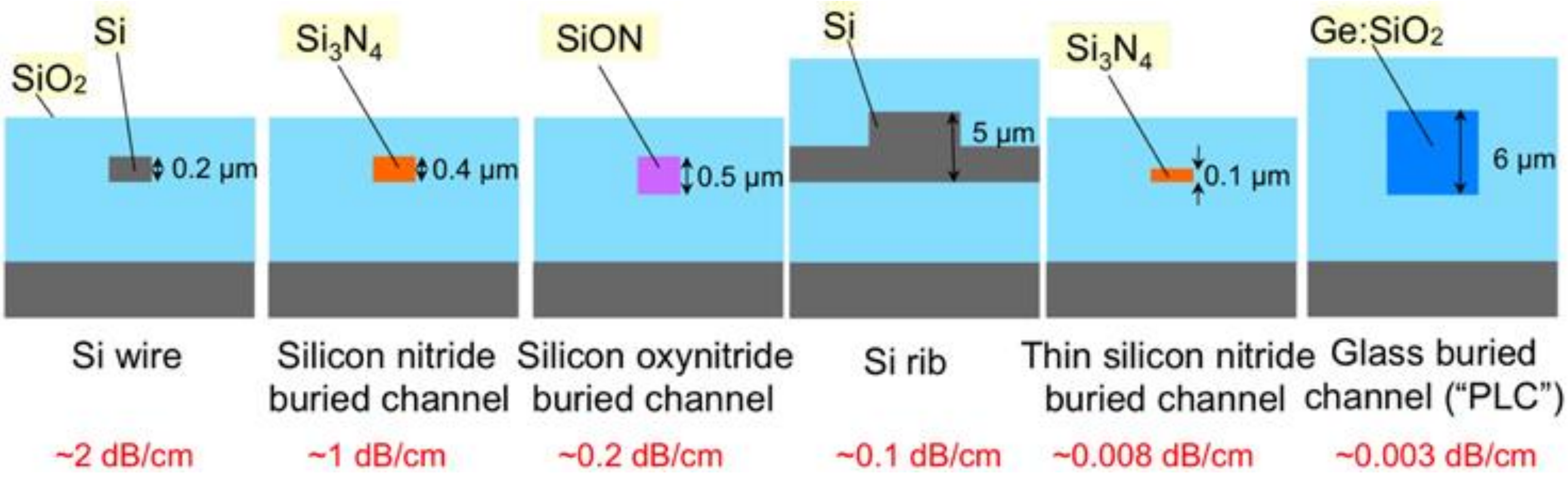
Silicon photonic waveguides and passive devices

Si: $n = 3.48$
SiO_2: $n = 1.45$
Si_3N_4: $n = 2.0$

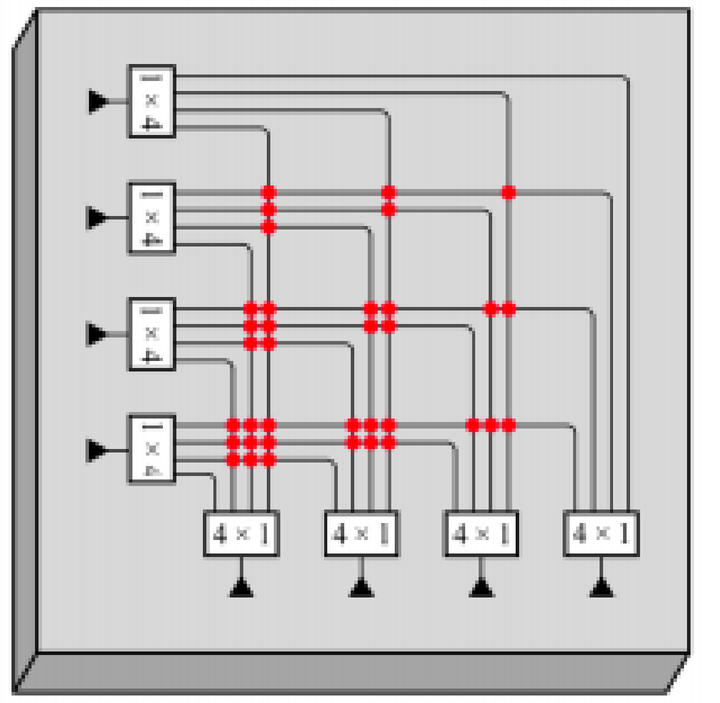


Standard designs of passive devices (bends, directional couplers, multi-mode interference couplers) are often offered in the process design kit (PDK).

Doerr et al., Frontiers in Physics, **3**, 37 (2015)

Multi-layer silicon photonic circuits

Example: Non-planar switch-and-select circuit



Number of waveguide crossings in planar circuit technology:

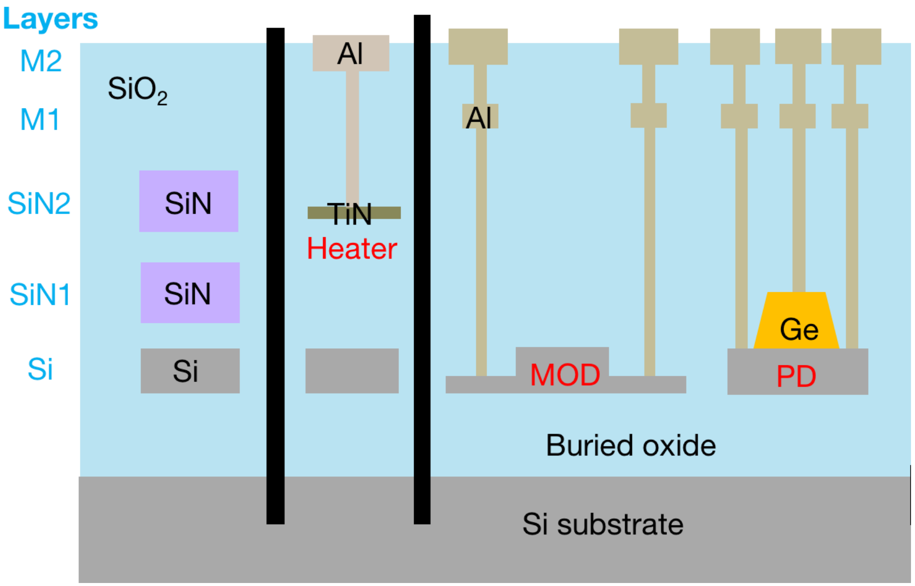
$$\eta_{n,n}^{(\text{basic})} = \left(\frac{n(n-1)}{2} \right)^2$$

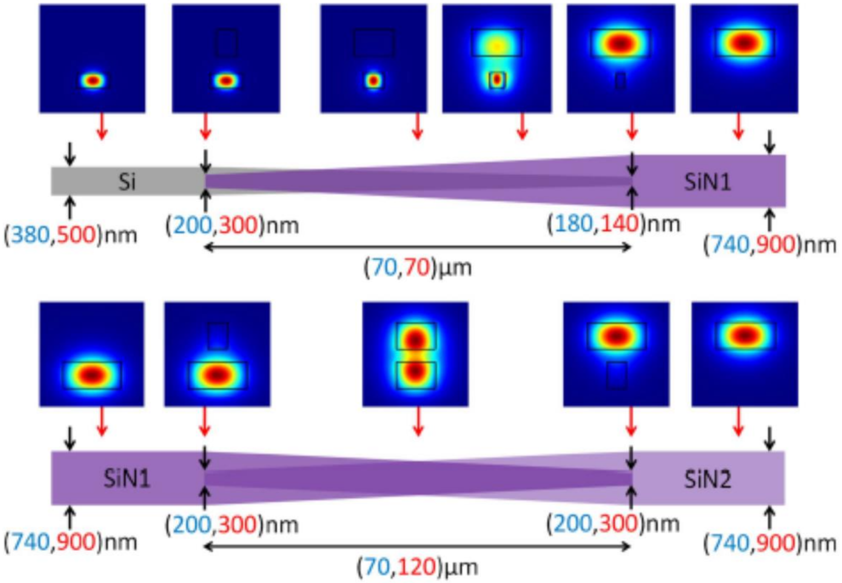
$\Rightarrow$ Avoid waveguide crossings by 3D overpasses

Nesic *et al.*, arXiv:1901.08309 (2019)

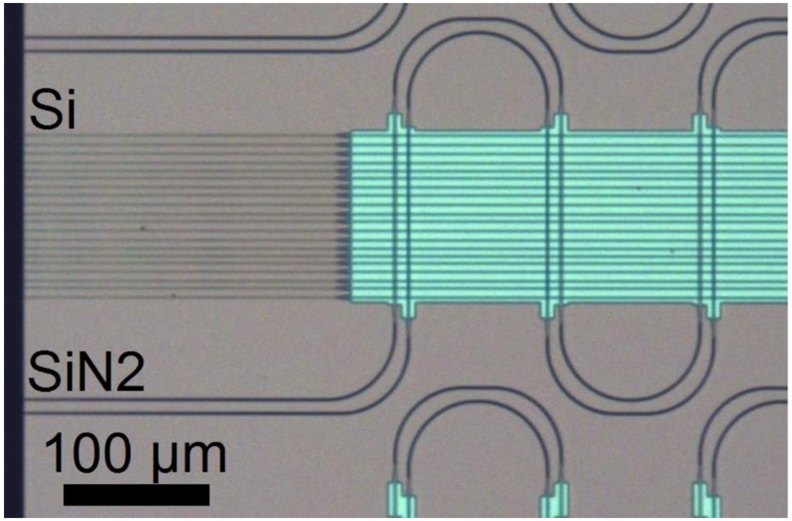
Sacher *et al.*, Proc. IEEE., 2232 – 2245 (2018)
Chiles *et al.*, APL Photonics 2(11), (2017).

Multi-layer silicon photonic circuits





- Up to 2 SiN waveguide layers integrated on Si using LPCVD (“FEOL”) or PECVD (“BEOL”)
- Adiabatic tapers for inter-layer power transfer
- Loss: < 3 mdB per crossing
- Crosstalk: < -60 dB



Sacher *et al.*, Proc. IEEE **106**, 2232 – 2245 (2018)

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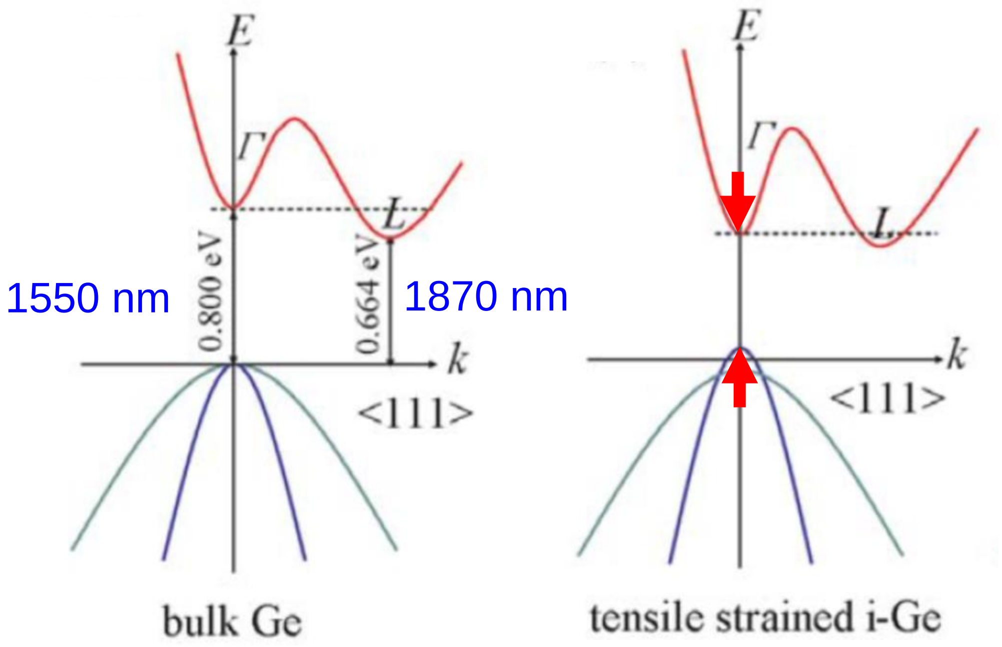
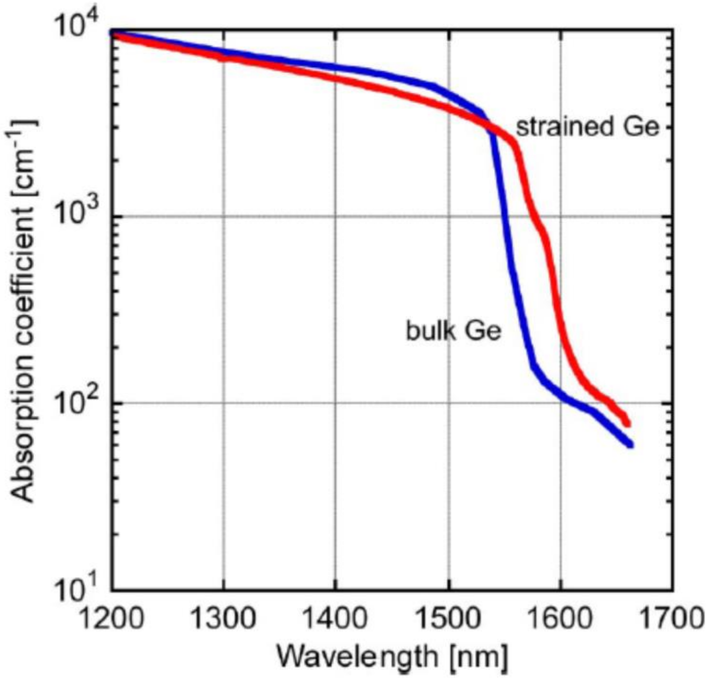
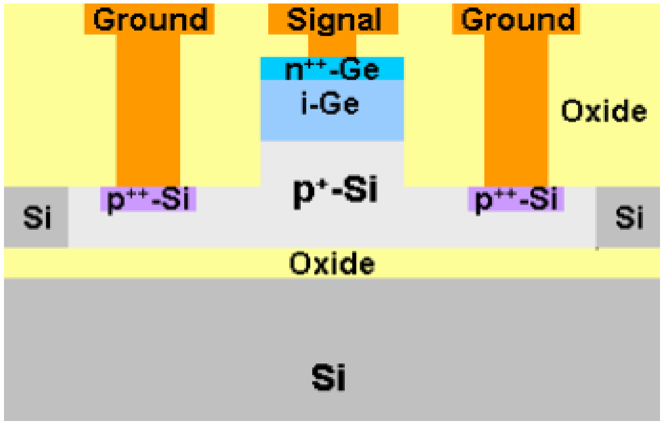
Silicon-germanium photodetectors



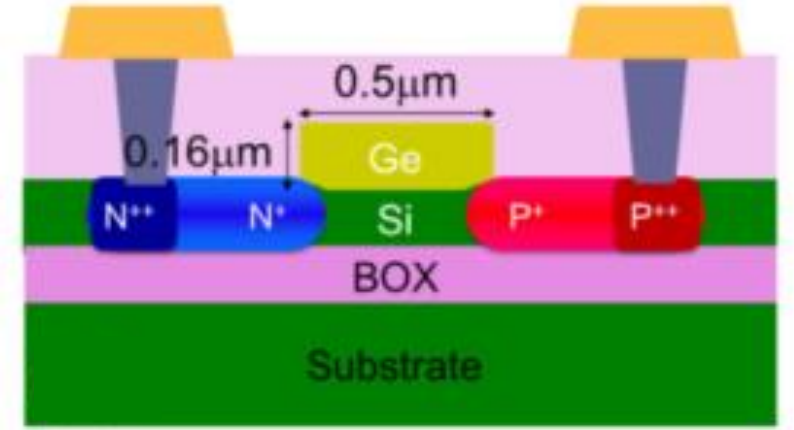


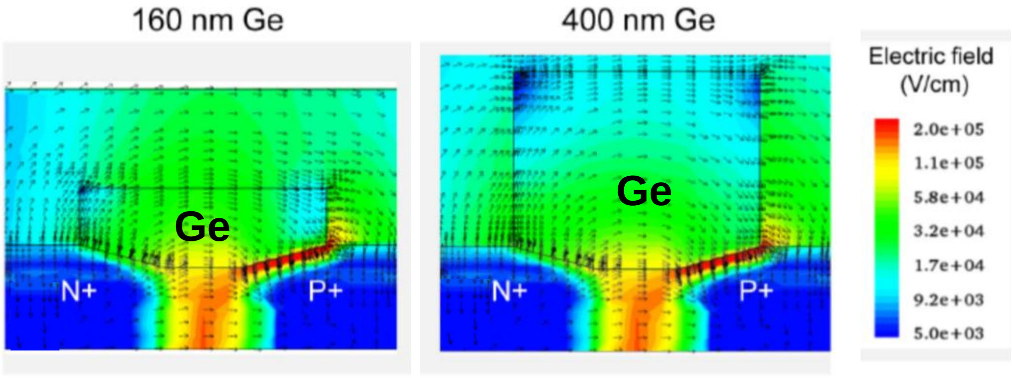


- Fabricated by SiGe heteroepitaxy
- Absorption at 1.55 µm enhanced by strain-induced reduction of the band spacing at the Γ-valley
- Responsivity: $1.16\ \mathrm{A/W}\ @\ \lambda = 1{,}55\ \mu\mathrm{m}$, $L = 20\ \mu\mathrm{m}$
- Bandwidth: $\sim 30\ \mathrm{GHz}\ @\ -2\ \mathrm{V}$ bias (limited by both transit time and RC time constant)

Sun *et al.*, ECS Transactions **16** (10) 881-889 (2008)
Colace *et al.*, IEEE Photonics Journal **1**, 69–79 (2009)
Yin *et al.*, Opt. Express **15**, 13965 - 13971 (2007)

Silicon-germanium photodetectors





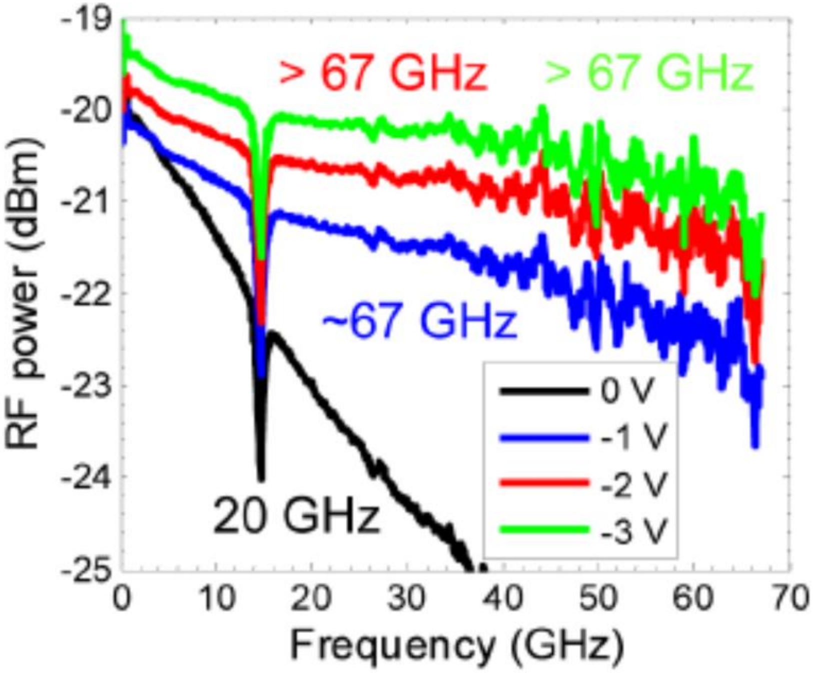
No metal contact on Ge

- → No light absorption from metal
  No doping of Ge required

Thin Ge layer (160 nm)

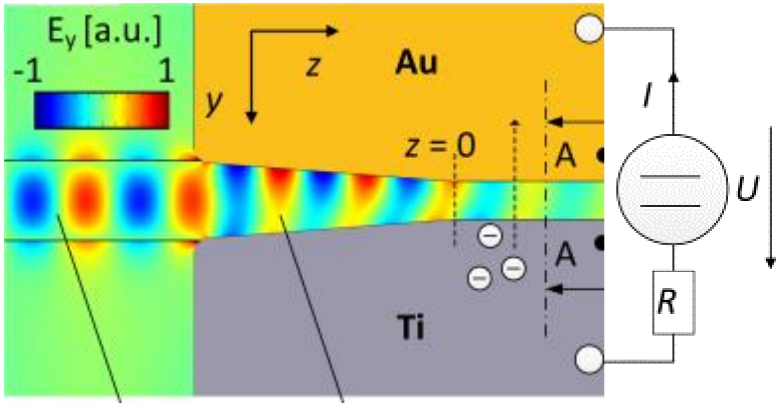
- → High electric field inside Ge:
  $E > 10^4$ V/cm @ 1 V bias
- → Carrier drift at saturation velocity for “CMOS-compatible” bias voltage.
- → f_{3dB} = 67 GHz, limited by transit time
  Potential to increase further

Responsivity: $0.74\ \mathrm{A/W}\ @\ \lambda = 1.55\ \mu\mathrm{m}$



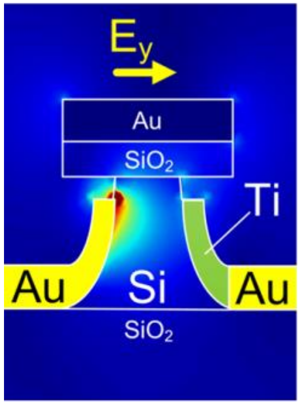
Chen *et al.*, Opt. Express **24**, 4622 - 4631 (2016)

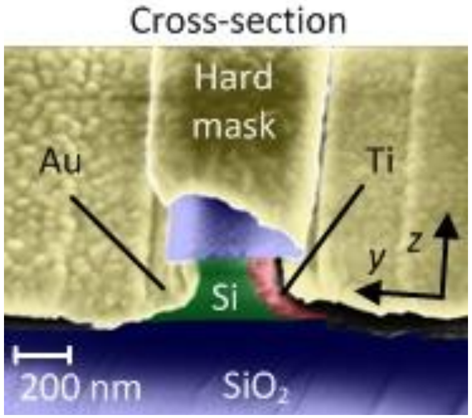
Plasmonic internal photoemission detectors (PIPED)



Si photonic waveguide

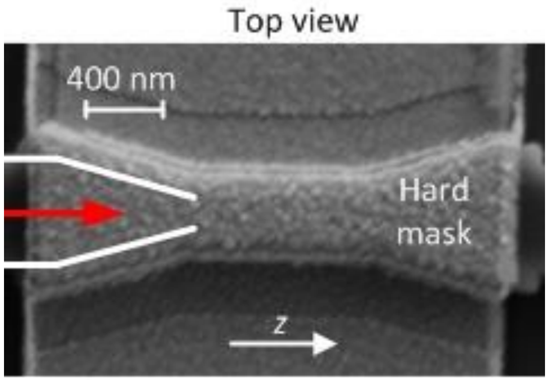
Photonic-to-plasmonic mode converter

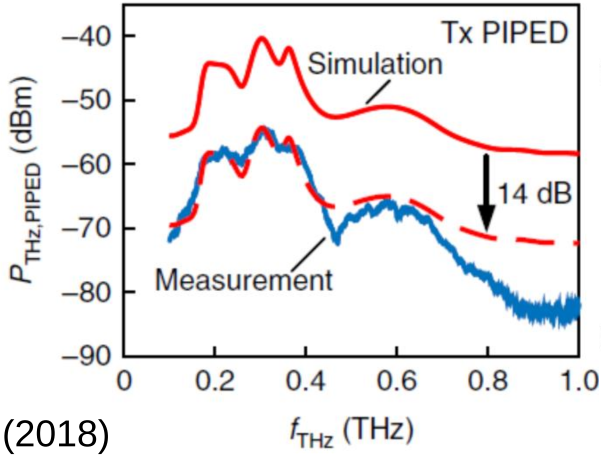


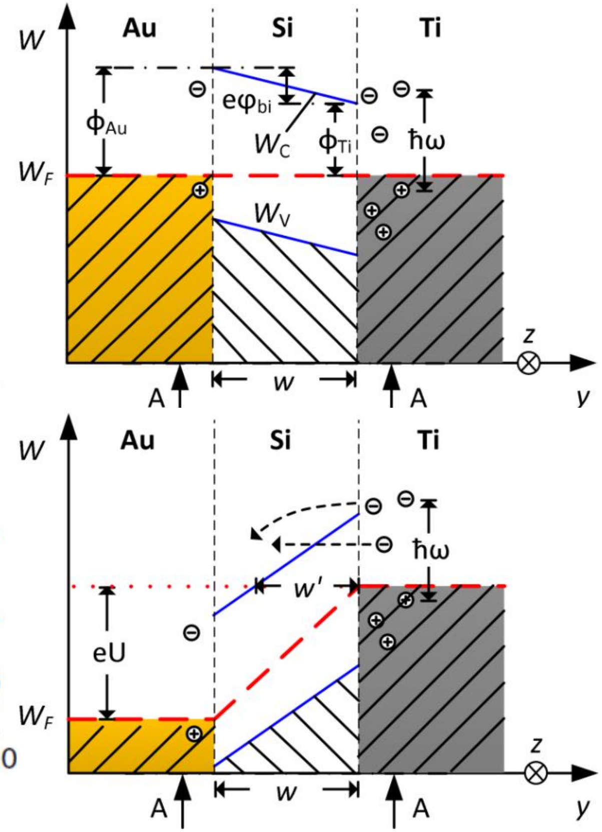


- Internal photoemission from Ti into adjacent ultra-thin Si drift region (~ 100 nm)
- Ultra-small lateral dimensions minimize capacitance (< 1 fF)

⇒ Ultra-fast response, enabling optoelectronic generation of THz signals

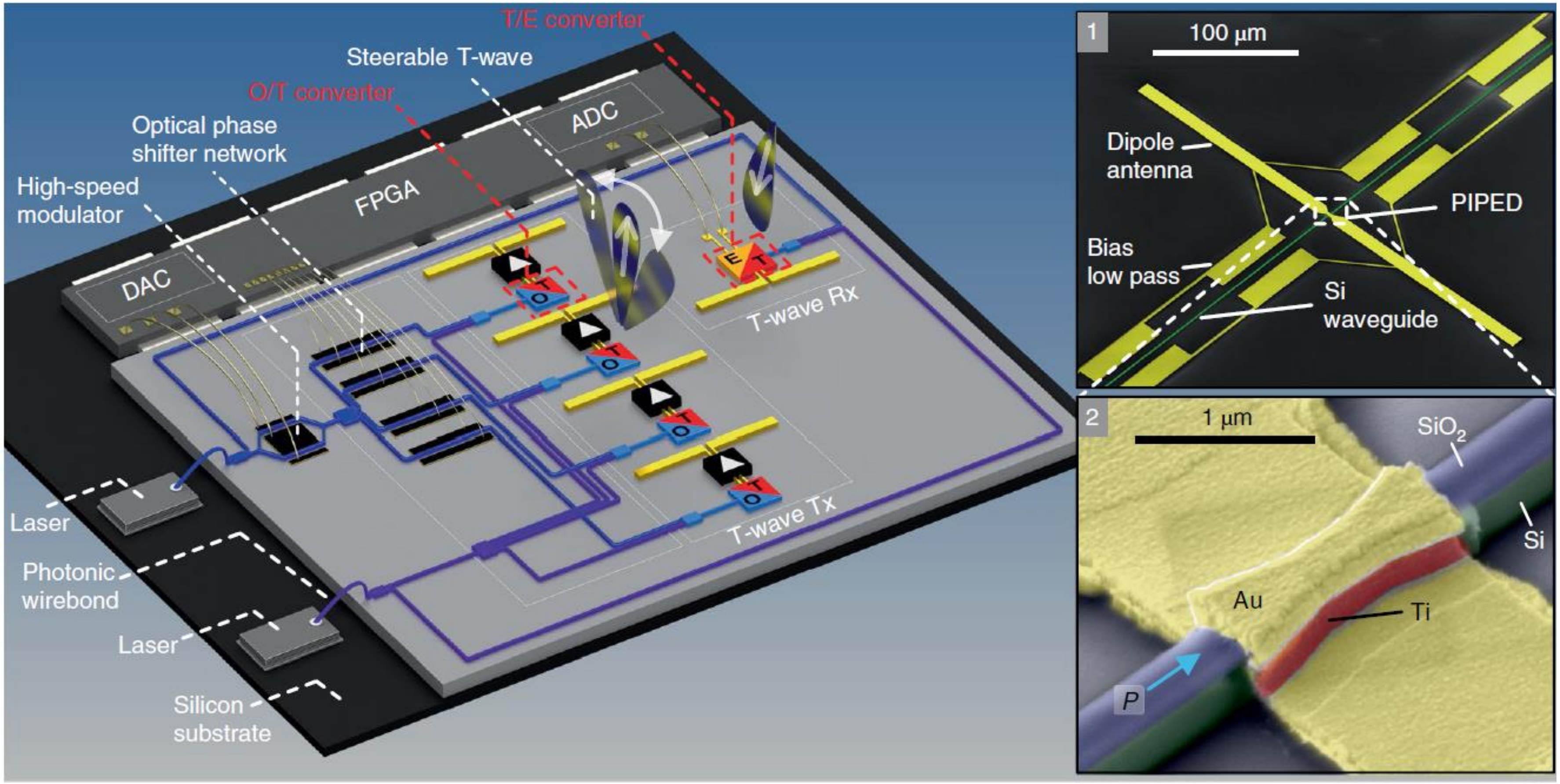






Muehlbrandt *et al.*, Optica **3**, 741 (2016)
Harter *et al.*, Nature Photonics **12**, 625-635 (2018)

Towards THz silicon photonics



Harter *et al*., Nature Photonics **12**, 625–633 (2018)

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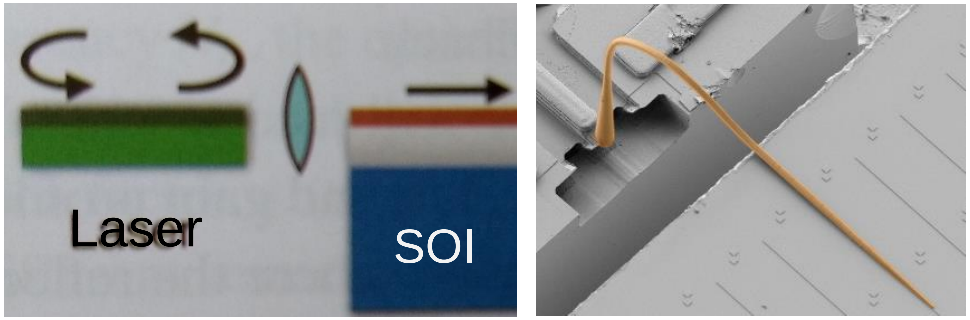
Light sources for silicon photonics

Co-packaging or hybrid multi-chip integration

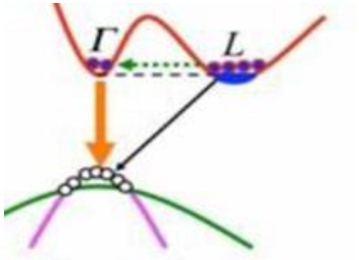
e.g., by high-precision alignment or by 3D-printed waveguides (“photonic wire bonds”)



Billah *et al.*, Optica **5**, 876-883 (2018)

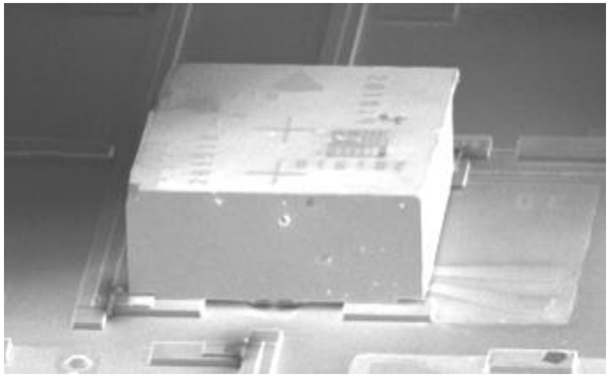
Monolithic integration

- Er-doped Si nanocrystals
  Zhizhong *et al.*, Proc. IEEE 97, 1250 (2009).
- Stimulated Raman scattering
  Rong *et al.*, Nature Phot. 1 232-237 (2007)
- Light emission in strained Ge
  Liu *et al.*, Opt. Lett. 35, 679–681 (2010)
- Epitaxial growth of III-V-materials on silicon



Mounting of pre-made lasers to SiP chip

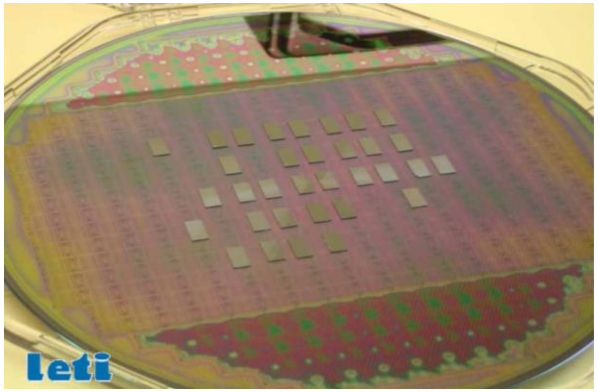
e.g., by active alignment



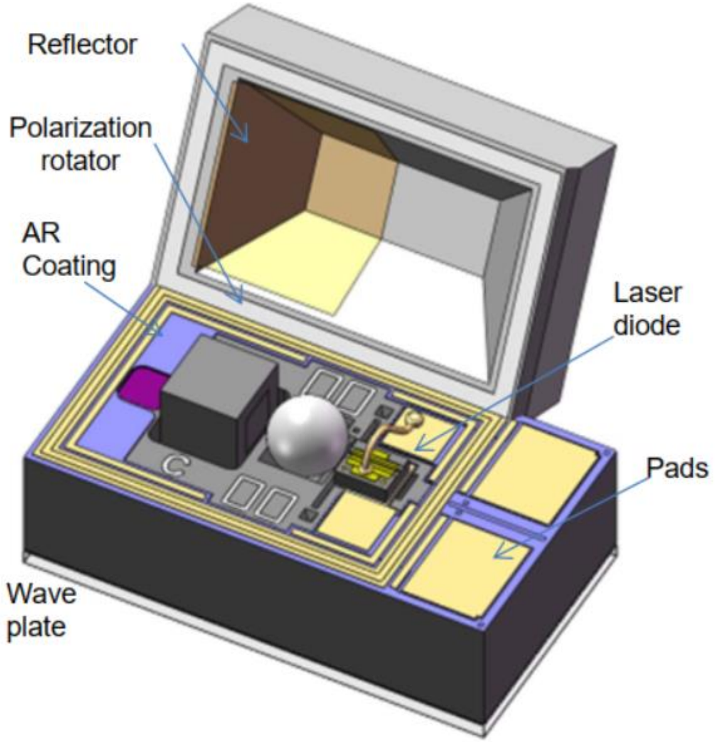
Mitze *et al.*, Int. Conf. on Group IV Phot. 2005

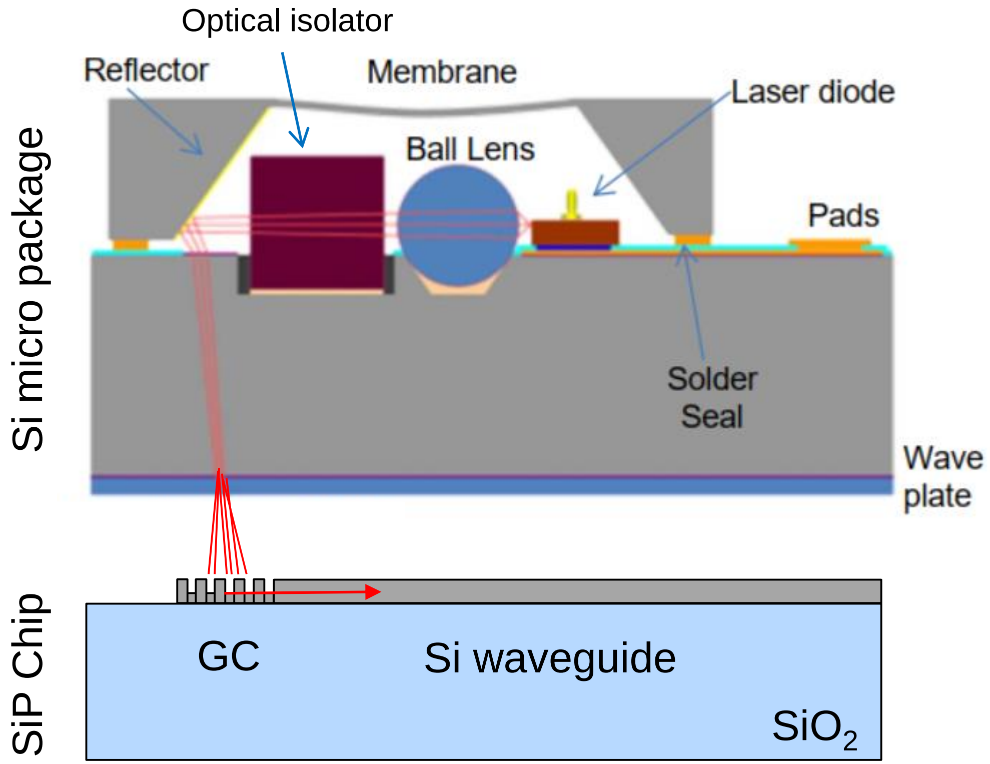
Heterogenous integration of III-V materials

Wafer-bonding of blank III-V-dies + collective processing



Integration of pre-fabricated lasers



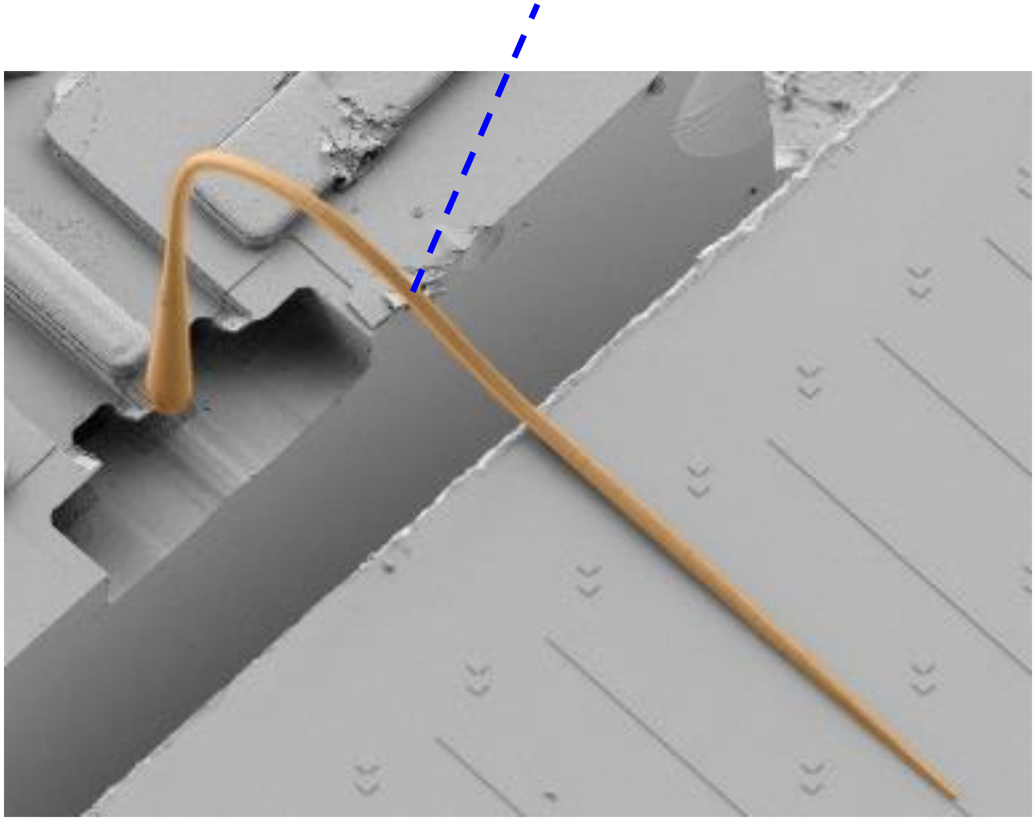


- Commercially used by Luxtera
- Silicon micro-machined laser diode housing for coupling, comprising lens and isolator
- Flexible: Use individually optimized laser diode from any supplier
- Allows for testing of devices prior to assembly
- Requires active alignment

Luxtera, *ECOC* (2014)
Snyder et al. al *J. Light. Technol.* **31** (2013)

Hybrid multi-chip integration by 3D nanoprinting

3D-printed „photonic wire bond“



vanguard AUTOMATION

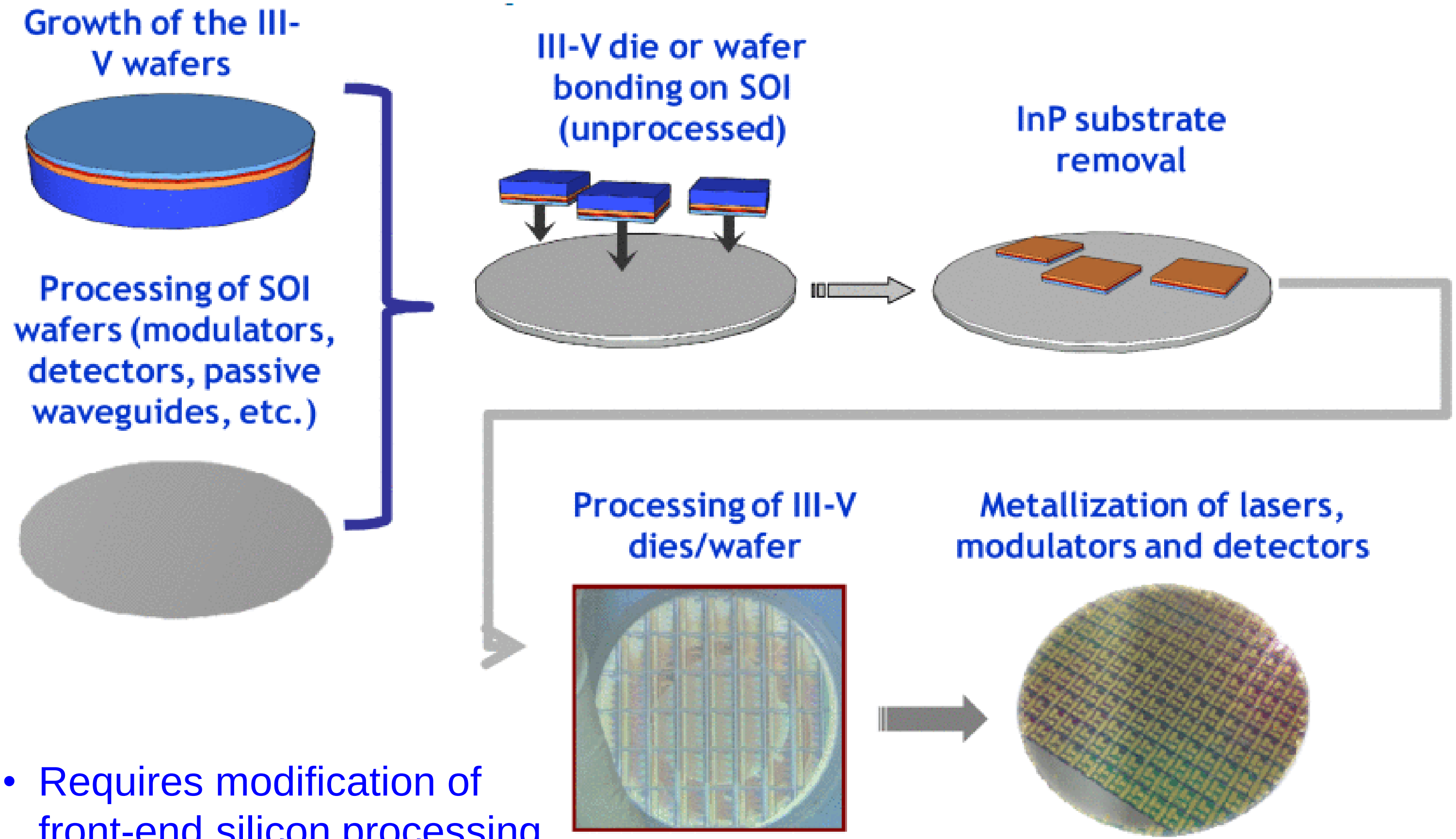
bright connections

Booth 5718

- Mounting of chips side-by-side (simplifies heat-sinking of laser)
- No active alignment required

Billah *et al.*, Optica **5**, 876-883 (2018)

Die-to-wafer bonding of III-V-materials



Growth of the III-V wafers

Processing of SOI wafers (modulators, detectors, passive waveguides, etc.)

III-V die or wafer bonding on SOI (unprocessed)

InP substrate removal

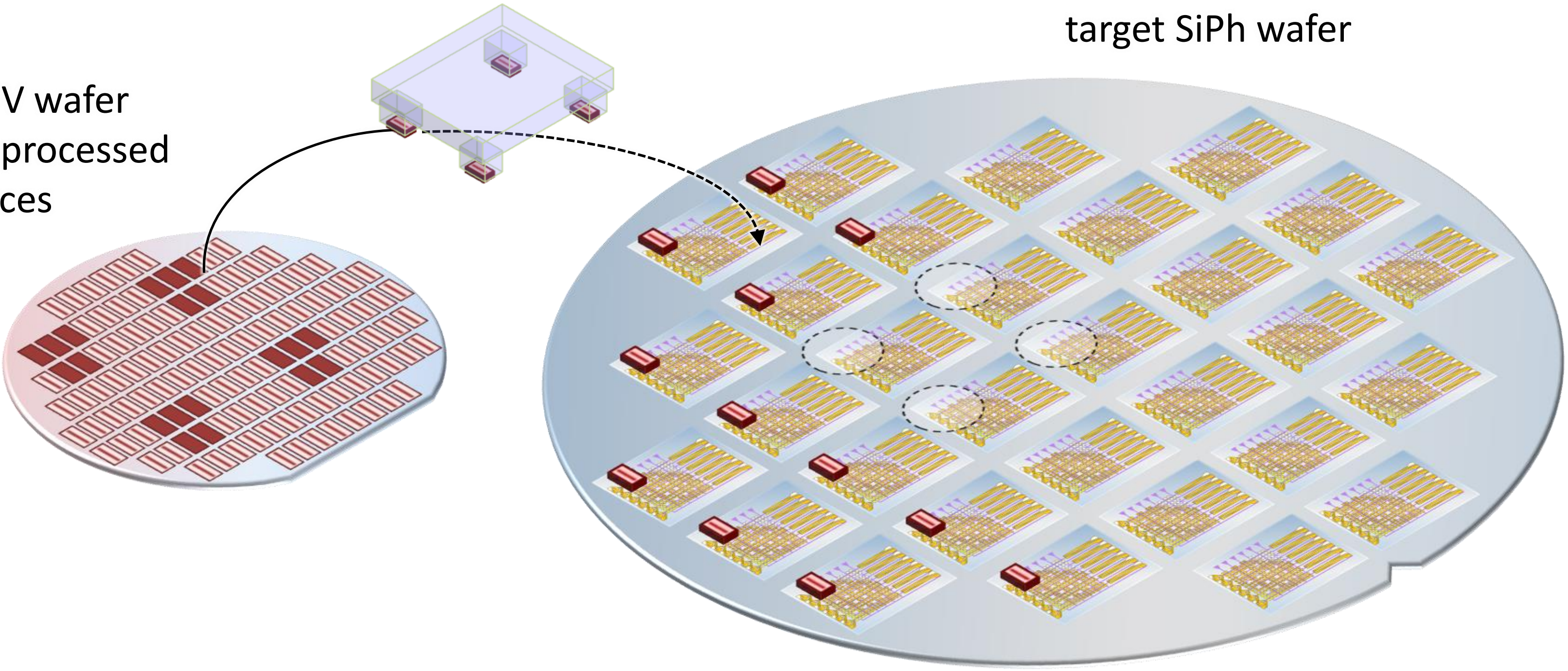
Processing of III-V dies/wafer

Metallization of lasers, modulators and detectors

- Requires modification of front-end silicon processing
- Performance comparable to native III-V-lasers / amplifiers
- Well suited for narrow-linewidth “external-cavity” lasers with high-Q resonator on silicon chip
- Used commercially, e.g., by Intel, Juniper Networks (former Aurrion) ….

Fang *et al.*, Opt. Express **14**, 9203–9210 (2006)
Campenhout *et al.*, Opt Express **15** , 6744-6749, (2007)
Roelkens *et al.*, Laser Photonics Rev. **4** (2010)
Duan *et al.*, IEEE J. Sel. Top. Quant. Elect.. **20,** 158-170 (2014)
Roelkens *et al.*, Photonics 2, 969–1004, 2015.

MICRO-TRANSFER-PRINTING



simultaneous transfer of
multiple coupons using
elastomer stamp

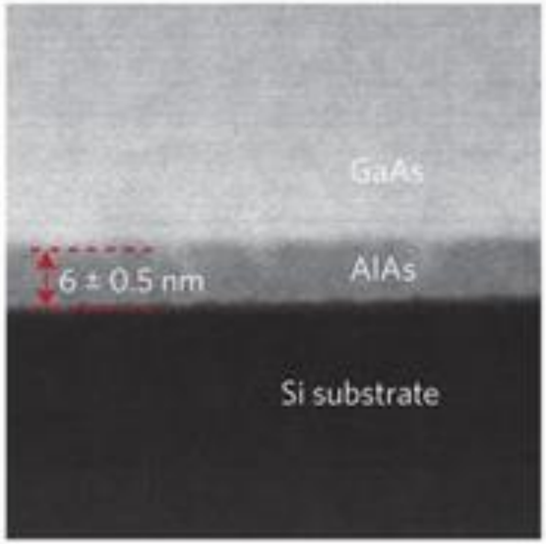
target SiPh wafer

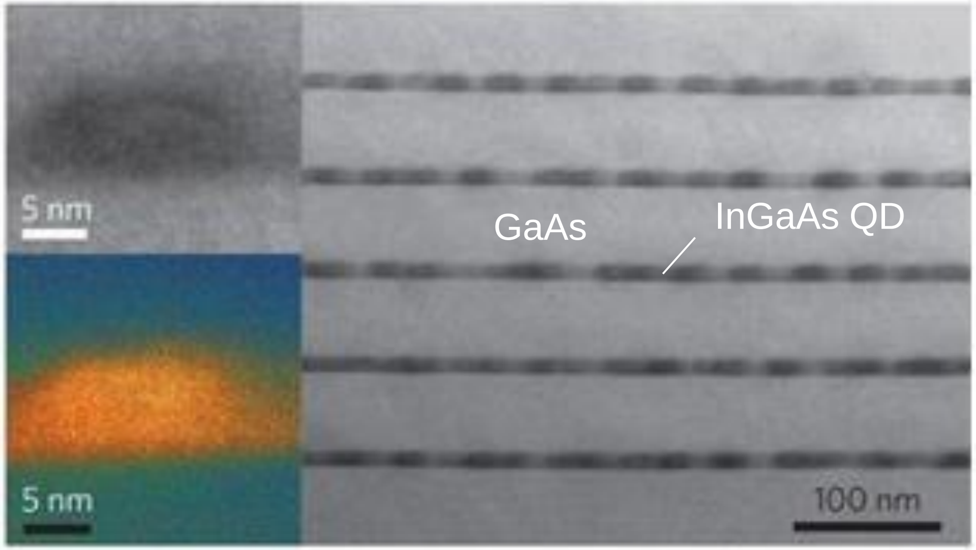
source III-V wafer
with fully processed
laser sources

µTP combines advantages of flip-chip and die-to-wafer bonding

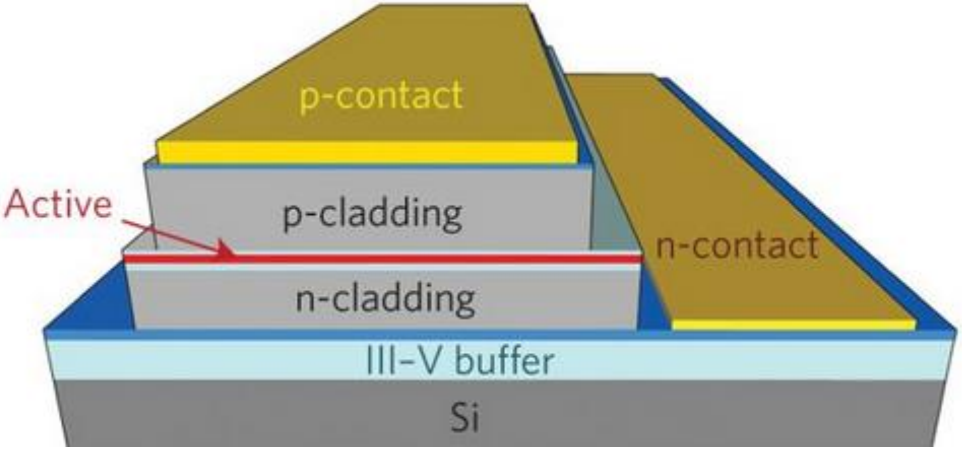
Slide courtesy of R. Baets / G. Roelkens

Epitaxial growth of III-V quantum dots (QD) on Si



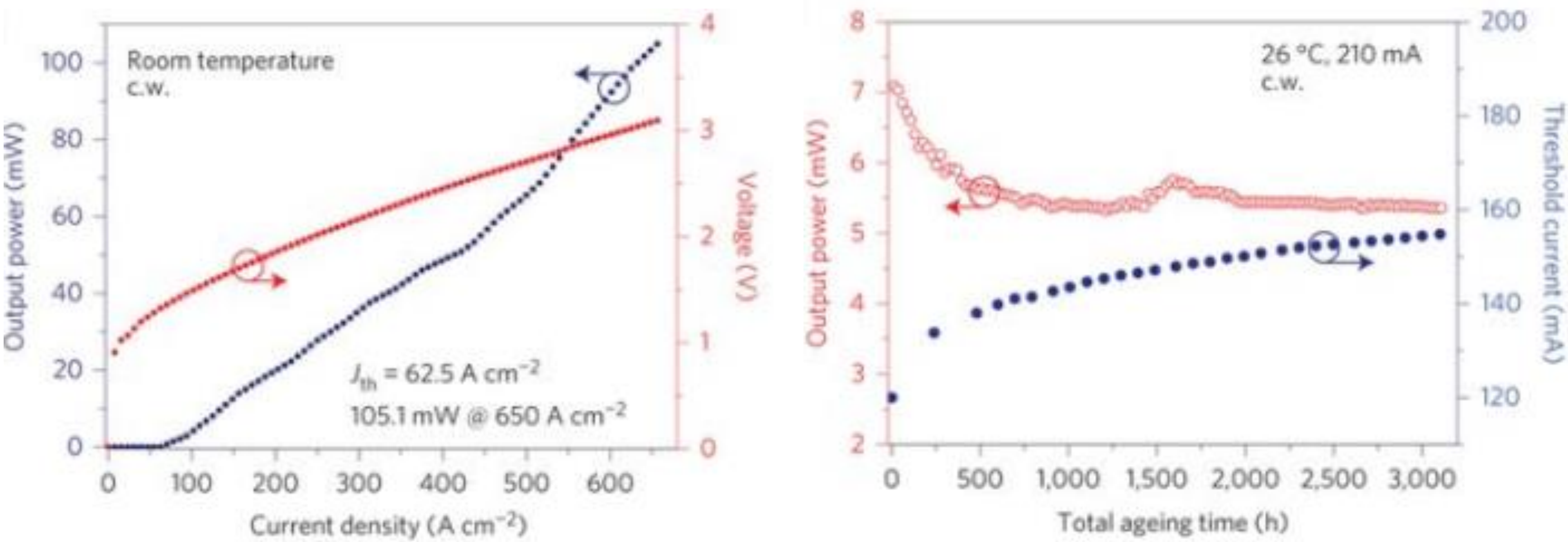


- 5 layers InGaAs/GaAs QD, grown on AlAs nucleation layer in Si
- Device fabricated by etching, metallization, cleaving



Chen *et al.*, *Nat. Photonics,* **10** (2016)

Epitaxial growth of III-V quantum dots (QD) on Si



Status: Strong performance parameters:

- Threshold current density < 100 A/cm^2
- Output power > 100 mW
- Operation up to 75° C
- Stable operation for > 3000h at 210 mA

Challenge: Integration of MBE growth into CMOS front-end processing

Chen *et al.*, *Nat. Photonics*, **10** (2016)

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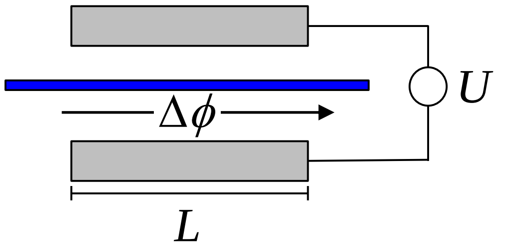
Phase modulators: Performance metrics

π-voltage: Voltage required for a phase shift of ΔΦ = π



(1) $$\Delta\phi = k_0 \Delta n_e L = \pi \frac{U}{U_\pi} \quad \text{for} \quad \Delta n_e \propto U \qquad [U_\pi] = 1\,\mathrm{V}$$

π-voltage-length product: Trade-off between operation voltage and device length

(2) $$\frac{1}{U_\pi L} = \frac{k_0}{\pi}\frac{\Delta n_\mathrm{e}}{U} \qquad [U_\pi L] = 1\,\mathrm{Vmm}$$

Voltage-loss product: Trade-off between operation voltage and optical insertion loss

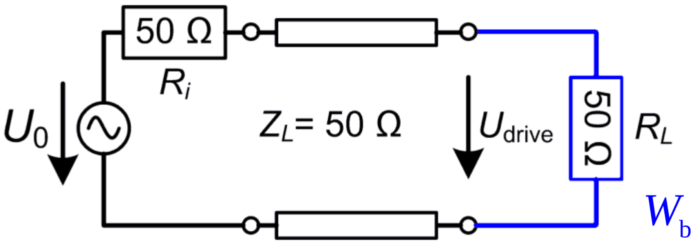
(3) $$a_\mathrm{dB} = -10\log(\mathrm{e}^{-\alpha L}) \approx 4.34\alpha L \qquad a_\mathrm{dB} U_\pi = \frac{4.34\alpha}{\frac{k_0}{\pi}\frac{\Delta n_\mathrm{e}}{U}}$$

$$[\alpha] = 1/\mathrm{m}$$

$$[a_\mathrm{dB} U_\pi] = 1\,\mathrm{V\,dB}$$

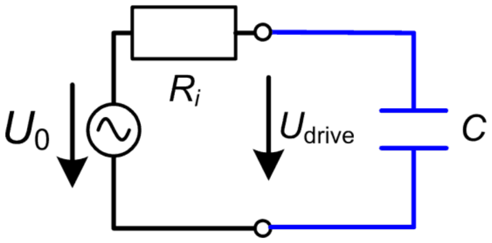
Power dissipation:

Travelling-wave modulator:



$$W_\mathrm{bit} = \frac{U_\mathrm{drive}^2 T_\mathrm{bit}}{4R}$$

Lumped-element (capacitive load):



$$W_\mathrm{bit} = \frac{C U_\mathrm{drive}^2}{4}$$

All-silicon phase shifters

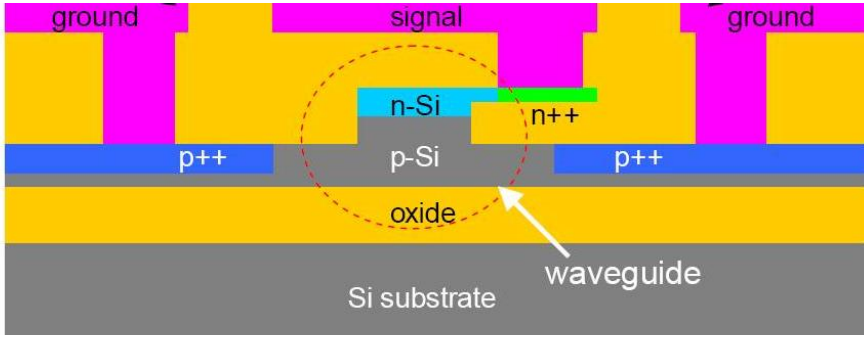
- Refractive index change induced by injection/removal of free electrons and holes

$$\Delta n = -(e^2\lambda^2/8\pi^2c^2\epsilon_0 n)\,[\Delta N_e/m_{ce}^{*} + \Delta N_h/m_{ch}^{*}]$$

$$\Delta\alpha = (e^3\lambda^2/4\pi^2c^3\epsilon_0 n)\,[\Delta N_e/m_{ce}^{*2}\mu_e + \Delta N_h/m_{ch}^{*2}\mu_h]$$

Soref *et al.*, IEEE J. Quantum Electron. **23**, 123–129, (1987)

- Carrier density modulation by depletion in reverse biased p-n-junctions or by carrier accumulation in silicon–insulator–silicon capacitors (SISCAP)



Liao *et al.*, Electron. Lett. 43, 1196 – 1197 (2007)
Liu *et al.*, Opt. Express 15, 660 – 668 (2007)

Depletion-layer width: $l = \sqrt{\frac{2\varepsilon_r\varepsilon_0}{e}(U_D - U)\left(\frac{1}{n_A} + \frac{1}{n_D}\right)}$ $\qquad U_D = U_T \ln\left(\frac{n_A n_D}{n_i^2}\right)$

All-silicon modulators phase shifters: Design principles

- Place carriers where they get dynamically depleted and actively contribute to index modulation
- Reduce carrier density elsewhere to the minimum required to ensure low RC time constant
- **Note:** Small device capacitance reduces $U_{\pi}L$, but increases RC time constant

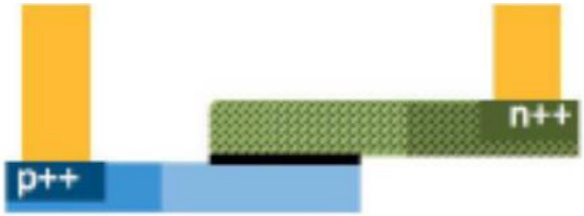
p-i-n-junction

p-i-p-i-n-junction

p-i-n-junction
w/ counter-doped corners

Vertical junction

All-around junction



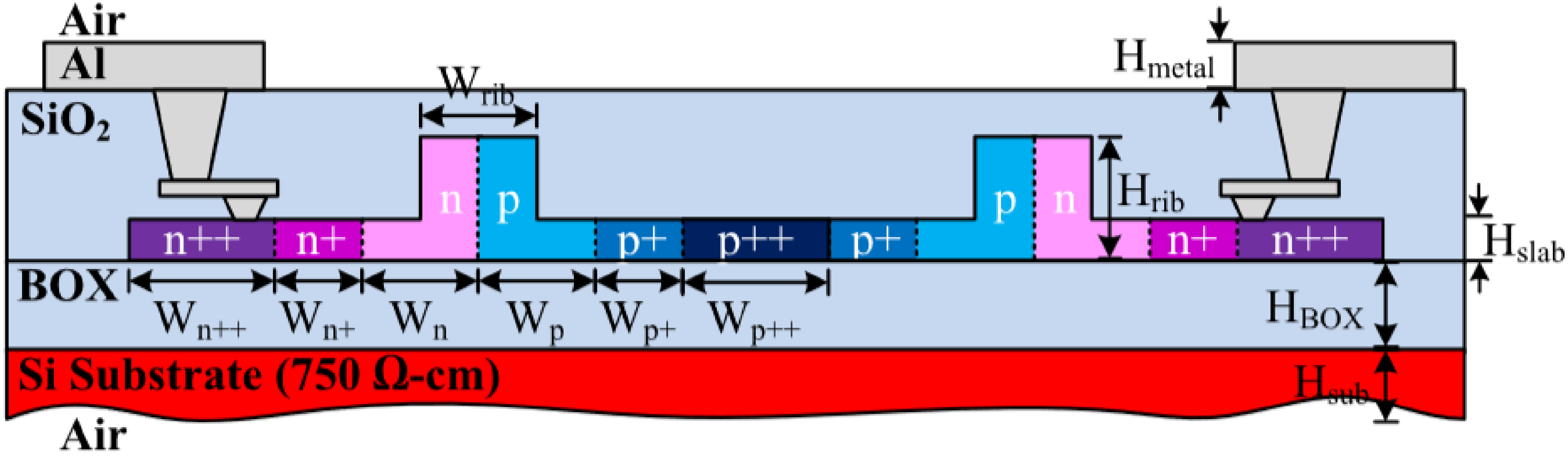
SISCAP

Interleaved *p-i-n*-junctions

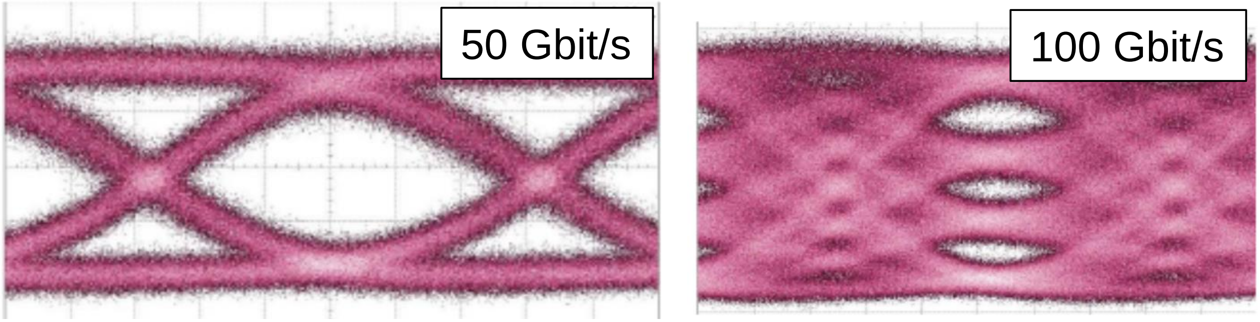
Intrinsic Si ■
Poly-Si ▨
p^- / p^+ doped Si ■ ■
n^- / n^+ doped Si ■ ■
Oxide ■
Contact Plug ■
E/O Polymer ▨

Witzens, IEEE Proc. **106**, 2158 – 2182 (2018)

Examples of all-silicon modulators



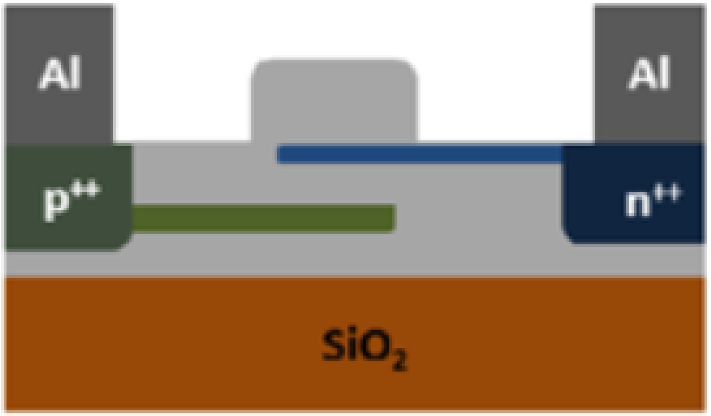
Reverse-biased p-n-junction: Small capacitance, high bandwidth

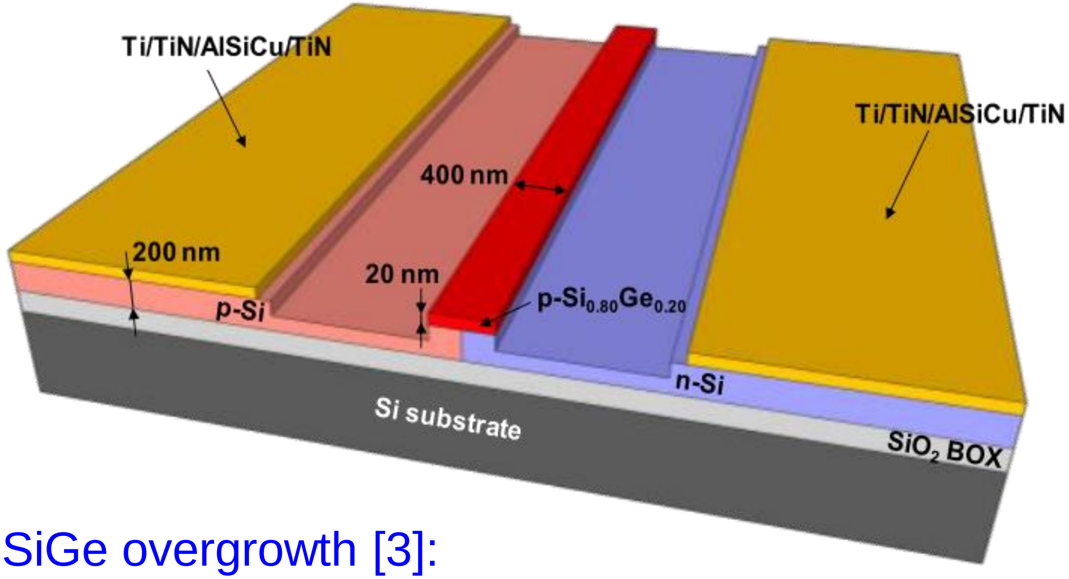


Technology		BW	$U_\pi L$	$a_{dB}U_\pi$
pn-type	[1]	**50 GHz**	25 Vmm	NA

[1] Patel *et al.*, Photon. Technol. Lett. **27**, 2015

Examples of all-silicon modulators





Vertical pn-junction [2]:

- Larger depletion volume, higher capacitance
- High doping to maintain bandwidth

SiGe overgrowth [3]:

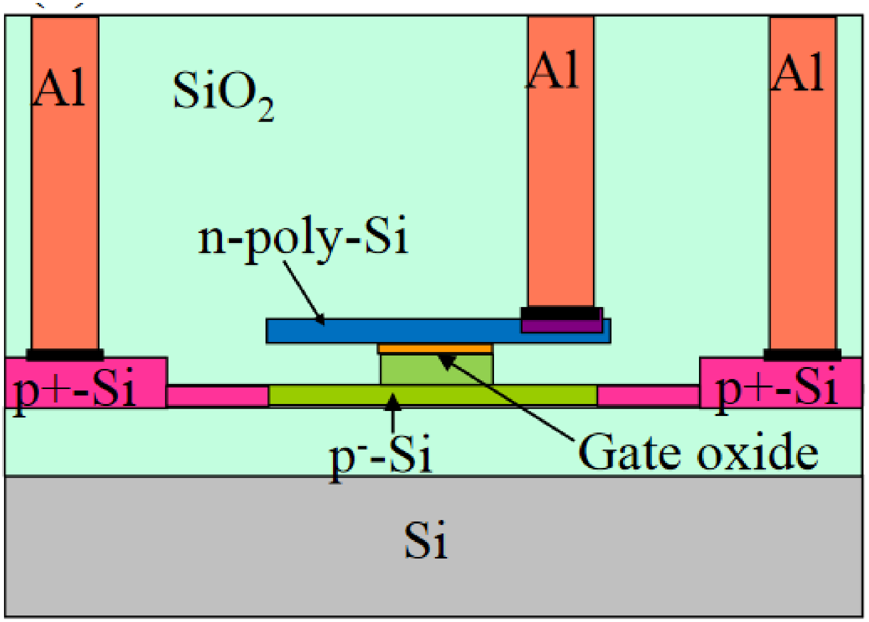
- Large depletion volume
- Strain leads to reduction of the hole effective mass, enhancing the change of refractive index and absorption

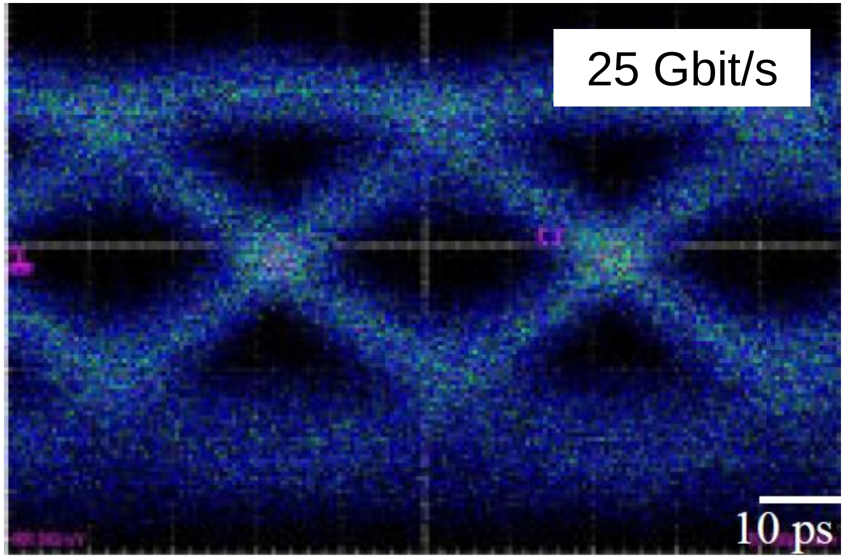
[2] Azadeh *et al.*, Opt. Express **23**, 23526 (2015)

[3] Fujikata *et al.*, *ECOC 2016,* Tu.3.A.4

Technology/FOM		BW	$U_\pi L$	$a_{dB}U_\pi$
pn-type (vertical)	[2]	**48 GHz**	**7.4 Vmm**	31 V dB
pn-type (SiGe)	[3]	~ 10 GHz	**6 Vmm**	12 V dB

SISCAP modulators





- Operated in accumulation mode.
- Weak doping allows to reduce losses.
- High capacitance leads to high efficiency, but increases RC time constant.

Technology		BW	$U_\pi L$	$a_{dB}U_\pi$
SISCAP	[4]	< 20 GHz	1.6 Vmm	5.6 V dB

[4] Fujikata *et al.*, Jpn. J. Appl. Phys. **55**, 2016

Hybrid modulators: III-V on silicon

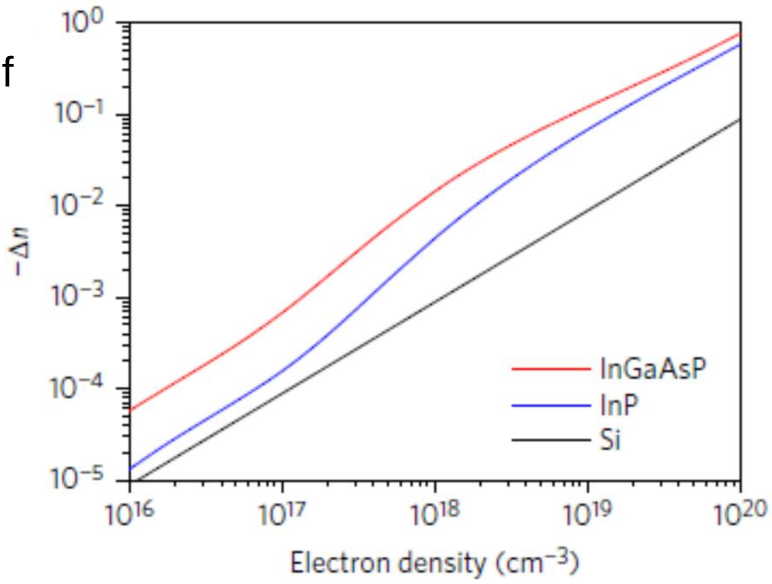
Magnitude of carrier-induced refraction Δn and absorption Δk depends on effective mass and mobility of the respective carrier type.

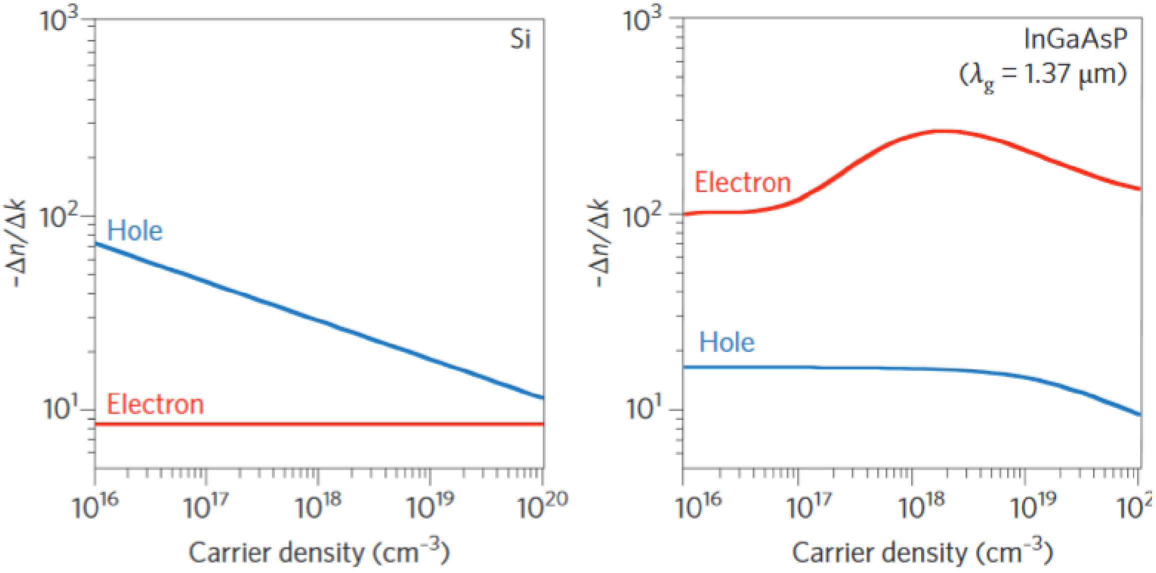
InGaAsP: Electrons favoured

- Stronger contribution Δn to refractive index than in Si
- Stronger relative contribution $\Delta n/\Delta k$

Silicon: Holes favoured due to stronger relative contribution $\Delta n/\Delta k$

⇒ Ideal: SISCAP structure with electrons in InGaAsP and holes in Si

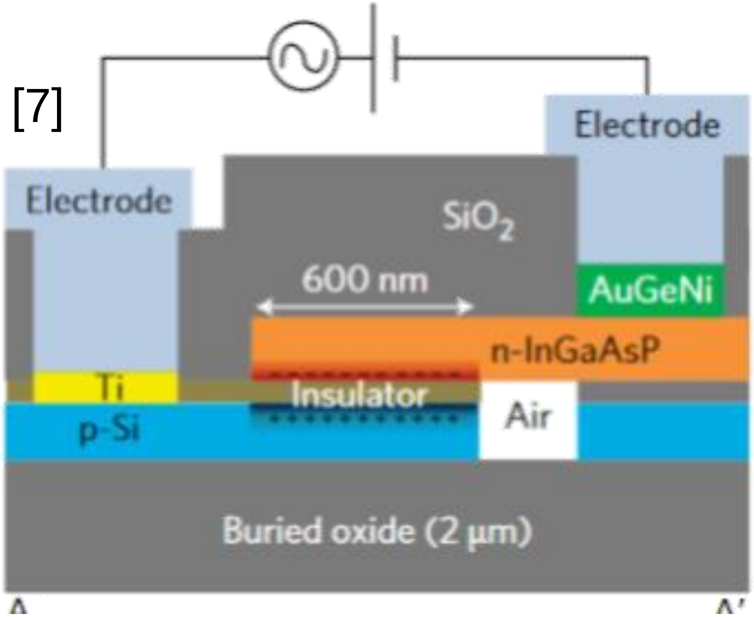




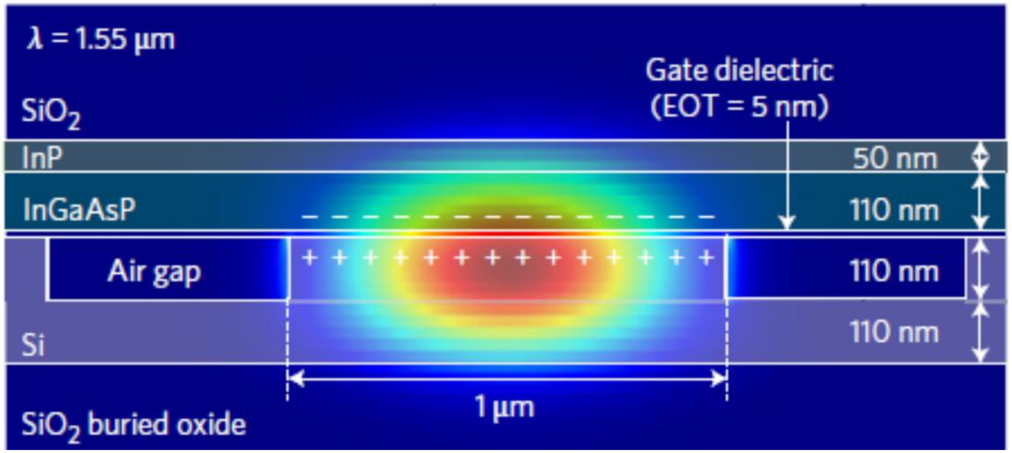
Witzens, Nature Photon. **11**, 459 (2017)
Hiraki *et al.*, Nature Photon. **11**, 482, (2017)
Han *et al.*, Nature Photon. **11**, 486, (2017)

SISCAP: III-V on Si

[7]



[8]

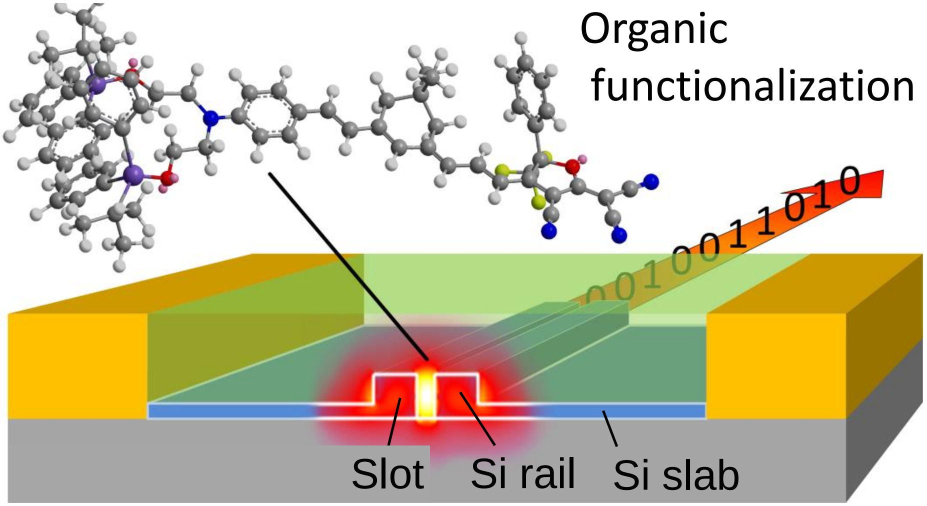


Technology		BW	$U_\pi L$	$a_{dB} U_\pi$
III-V on Si	[5]	2.2 GHz*	0.9 Vmm	4 V dB
III-V on Si	[6]	100 MHz*	0.47 Vmm	0.9 V dB

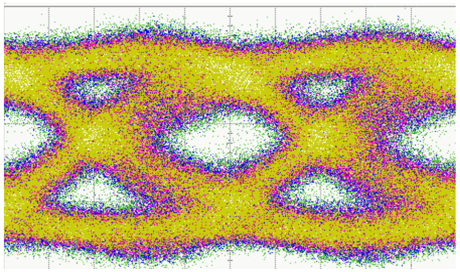
[5] Hiraki *et al.*, Nature Photon. **11**, 482, 2017
[6] Han *et al.*, Nature Photon. **11**, 486, 2017

* Currently limited by contact resistance (not fundamental!)

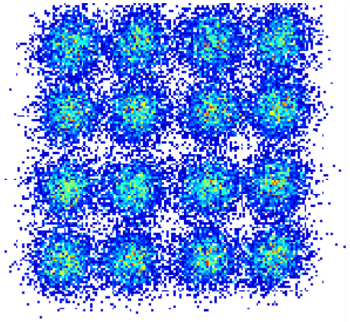
Silicon-Organic Hybrid (SOH) Electro-Optic Modulators

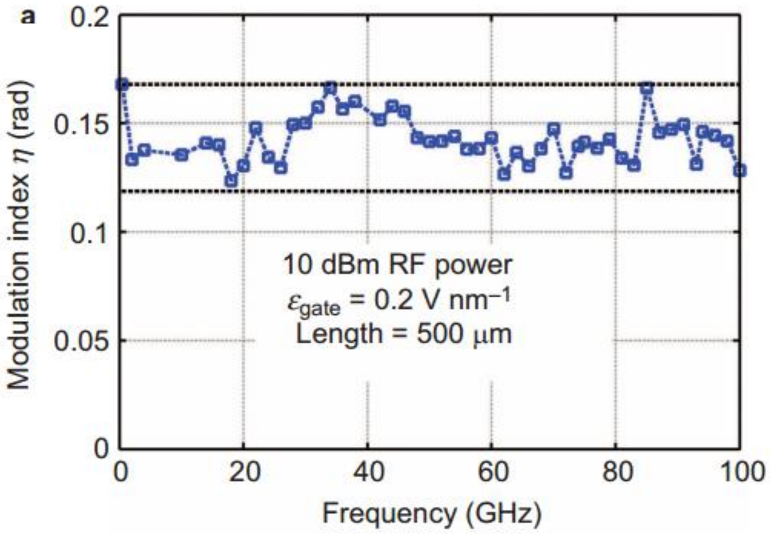


100 Gbit/s OOK



100 GBd 16 QAM



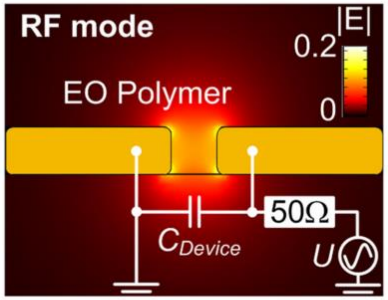


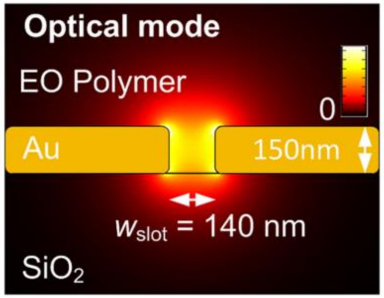
- Concept: Combine silicon-on-insulator waveguides with organic electro-optic cladding material
- Highly efficient materials obtained by theory-guided molecular design: r_{33} = 390 pm/V, $U_\pi L \approx 0.3$ Vmm
- Can be realized by back-end-of-line processing

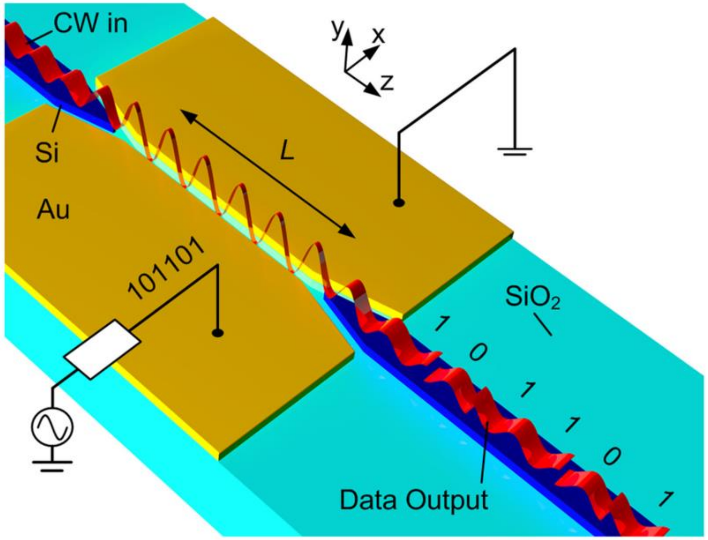
		BW	$U_\pi L$	$a_{dB}U_\pi$
SOH	[10]	20 GHz	**0.32 Vmm**	**1.2 V dB**

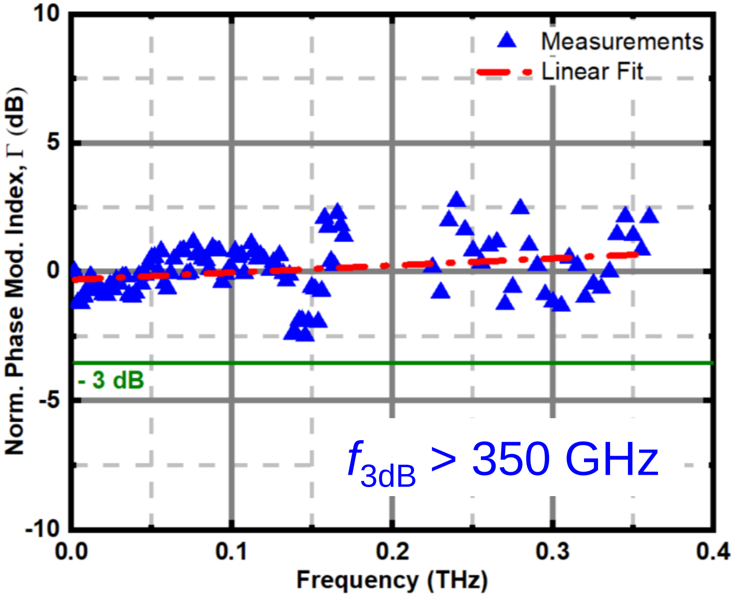
[8] Koos *et al*., J. Lightw. Technol. **24**, 256-268 (2016)
[9] Alloatti *et. al*., Light Sci. Appl. **3** (2014)
[10] Kieninger *et al.,* Optica **5**, 739 - 748 (2018)
[11] Wolf *et al*., Opt. Express **26**, 220-232 (2018)
[12] Wolf *et al*., Scientific Reports **8**, 2598-1 – 2598-13 (2018)

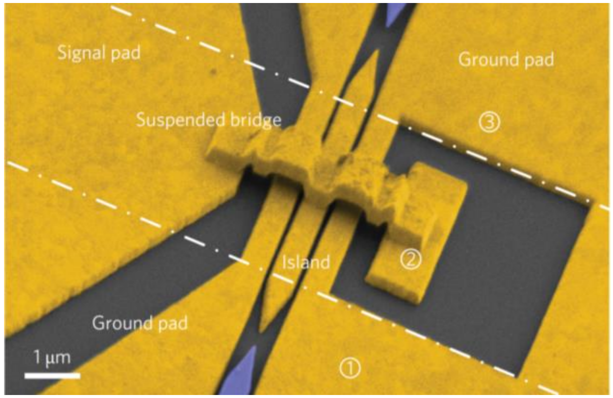
Plasmonic-organic hybrid (POH) modulators











Technology	Ref	BW	$U_\pi L$	$a_{dB}U_\pi$
POH	[12]	> 70 GHz	0.06 Vmm	96 V dB
POH	[13]	NA	0.05 Vmm	22 V dB
POH	[14]	> 170 GHz	~0.1Vmm	~30 V dB

[11] Melikyan et al. *Nature Photonics* **8** (3) p 229 (2014)
[12] Haffner, C. et al. *Nature Photonics* **9** (8) p 525 (2015)

[13] Heni W. et al. *Optics Express* **25** (3) p 2627 (2017)
[14] Hoessbacher et al., Opt. Express **25**, 1762 (2017)
[15] Ummethala S. et al., Cleo 2018, paper STu3D.4

Overview: Performance of hybrid and all-silicon modulators

Technology		BW	$U_\pi L$	$a_{dB}U_\pi$	*Process modifications beyond standard silicon photonics*
pn-type	[1]	50 GHz	25 Vmm	NA	None
pn-type (vertical)	[2]	48 GHz	7.4 Vmm	31 V dB	None
pn-type (SiGe)	[3]	~ 10 GHz	6 Vmm	12 V dB	None
SISCAP	[4]	< 20 GHz	1.6 Vmm	5.6 V dB	None
SOH	[9]	100 GHz	11 Vmm	55 V dB	BEOL post-processing
SOH	[10]	20 GHz	0.32 Vmm	1.2 V dB	BEOL post-processing
III-V on Si	[5]	2.2 GHz	0.9 Vmm	4 V dB	New process
III-V on Si	[6]	0.2 GHz	0.47 Vmm	0.9 V dB	New process
POH	[12]	> 70 GHz	0.06 Vmm	96 V dB	New process
POH	[13]	NA	0.05 Vmm	22 V dB	New process
POH	[14]	> 170 GHz	~0.1 Vmm	~30 V dB	New process
Si-BTO	[7]	30 GHz	4.5 Vmm	4.5 V dB	New process
$LiNb0_3$ on Si	[16]	100 GHz	22 Vmm	0.44 V dB	New process

[7] Abel *et al.*, Nature Materials **18**, 42 (2019)

[16] Wang *et al.*, Nature **562**, 101-104, 2018

Silicon Photonics, Hybrid Integration, and Frequency Combs: Technologies for High-Bandwidth Communications

Introduction

- Scalability challenges in optical communications
- Silicon photonics and the need for hybrid integration

Silicon-based building blocks for high-bandwidth transceivers

- Waveguides and passive devices
- Photodetectors
- Light sources
- Modulators

Packaging and system assembly

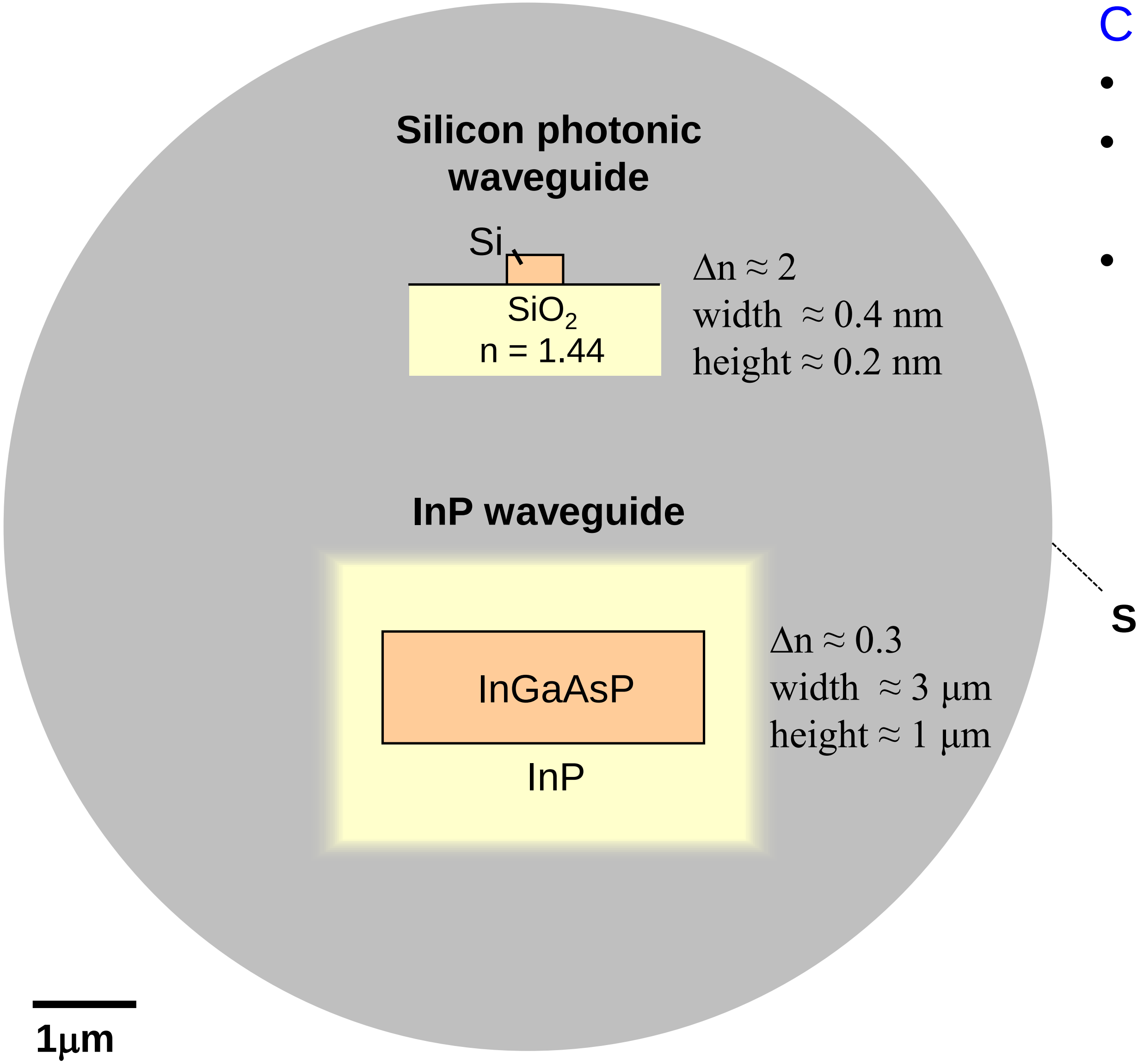
- Coupling interfaces to silicon photonic waveguides
- In-situ waveguide fabrication by 3D laser lithography

Silicon photonic transceivers

- Commercial products and experimental demonstrations
- Towards massively parallel WDM transceivers

Summary

Packaging and assembly challenges



Single-mode fiber core

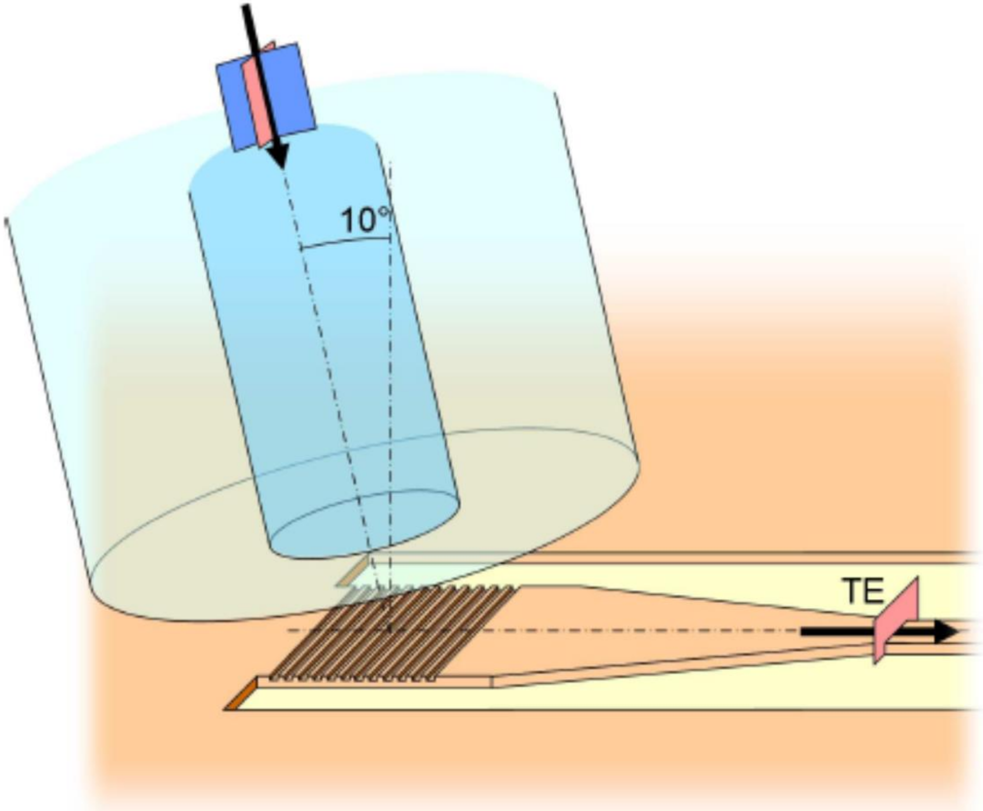
$\Delta n \approx 10^{-3}$

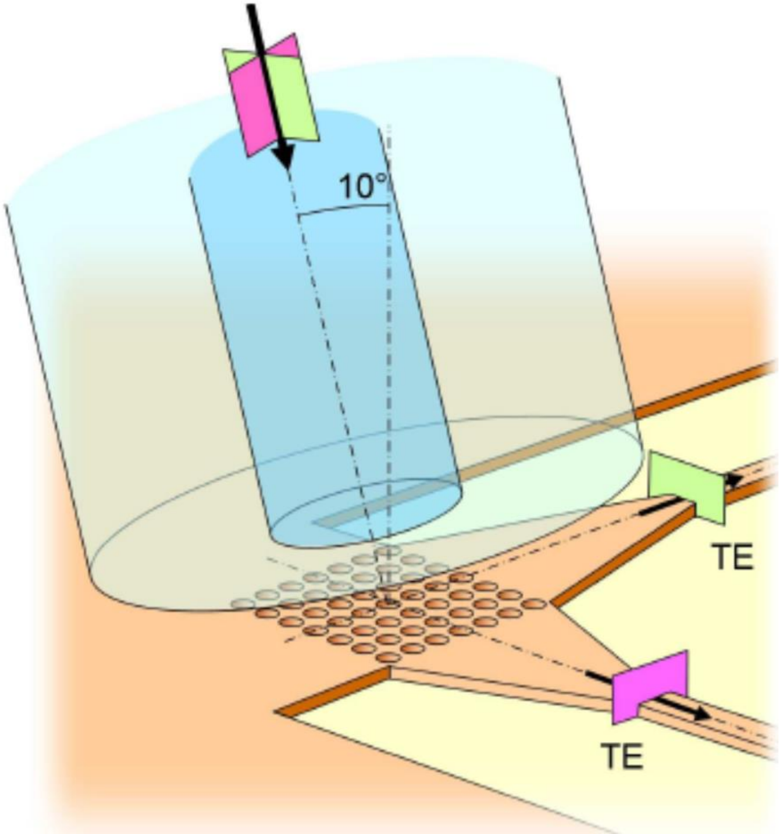
$\varnothing \approx 10$ µm

Challenges:

- Mode matching
- High-precision active alignment
- Polarization handling

Grating couplers



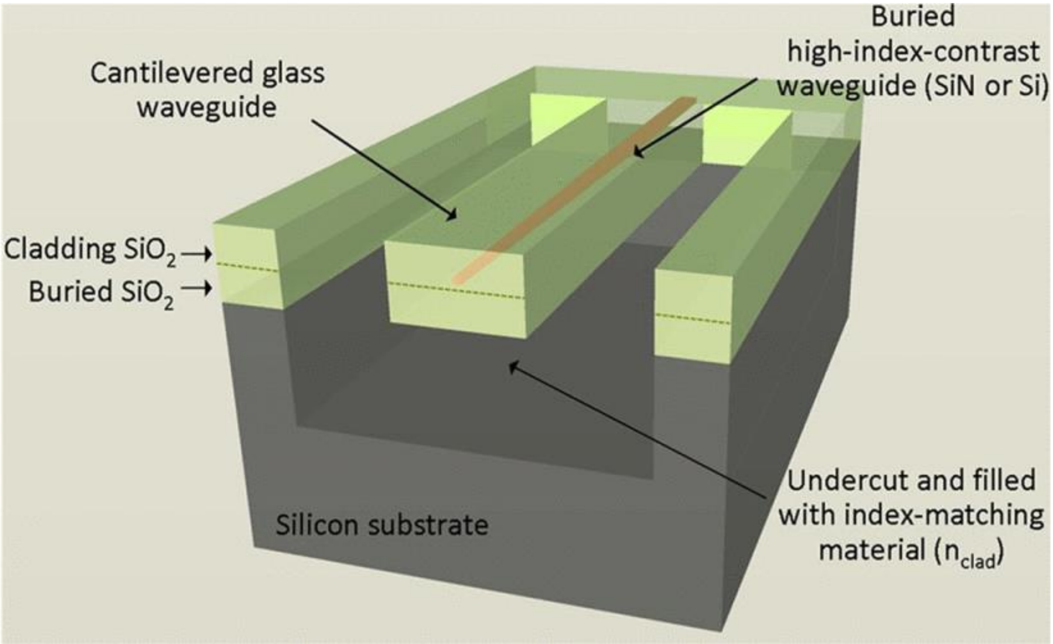


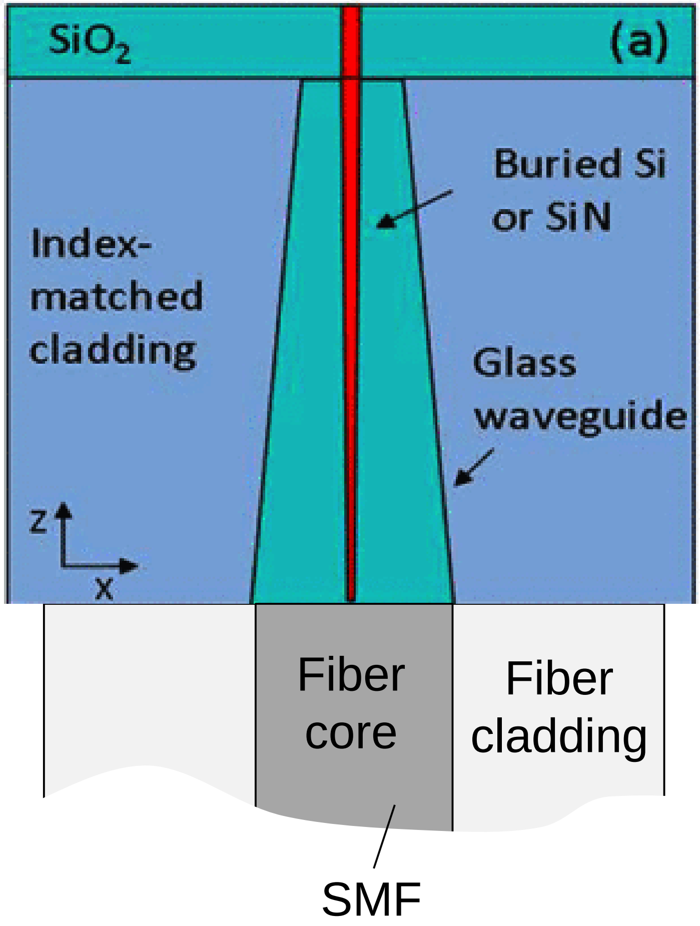
- Chip-level testing
- Coupling loss 0.5 … 4.5 dB (0.5 dB backside mirror)
- Bandwidth typ. 40 nm
- Single polarization

- Polarization splitting

Bogaerts *et al.*, Opt. Express **15**, 1567-1578, (2007)
Laere *et al.*, IEEE Photon. Technol. Lett. **20**, 318-320 (2008)
Zaoui *et al.*, IEEE Photon. Technol. Lett. **25**, 1277-1286 (2013)

Edge couplers





- Coupling loss 0.5 … 2 dB
- Bandwidth 300 nm
- PDL 0.5 dB

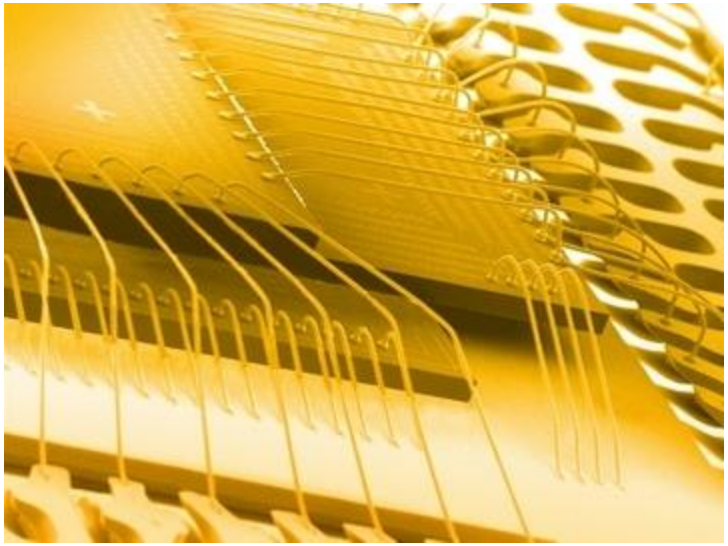
Note: System assembly still requires precise (active) alignment

Chen *et al.*, IEEE Photon. Technol. Lett. **22** (2010)
Pu, et al., *Opt. Commun.* **283**, 3678–3682, (2010)
Fang et al. *Opt. Express* **19**, 21588–21594 (2011)

Integrated polarization rotators:

Fukuda *et al.*, Opt. Express **16**, 2628-2635 (2008)
Watts *at al.*, Opt. Lett. **30**, 138-140 (2005)
Chen et al. Opt.. Lett. **36**, 469-471 (2011)

Wire bonding in electronics … and photonics!



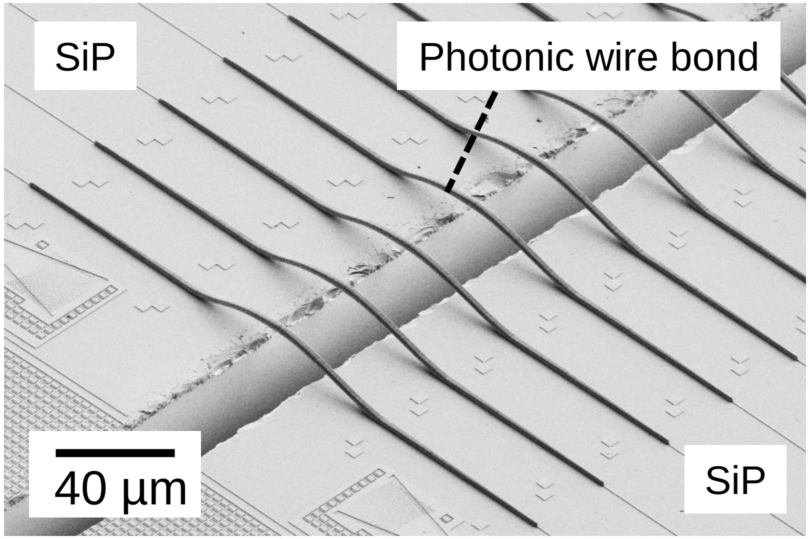
Electronic wire bonding: Stacked-die package

- Highly scalable automated fabrication (10's of connections per second)
- Tight control of the loop trajectory

Picture source: Kulicke & Soffa, http://www.kns.com/

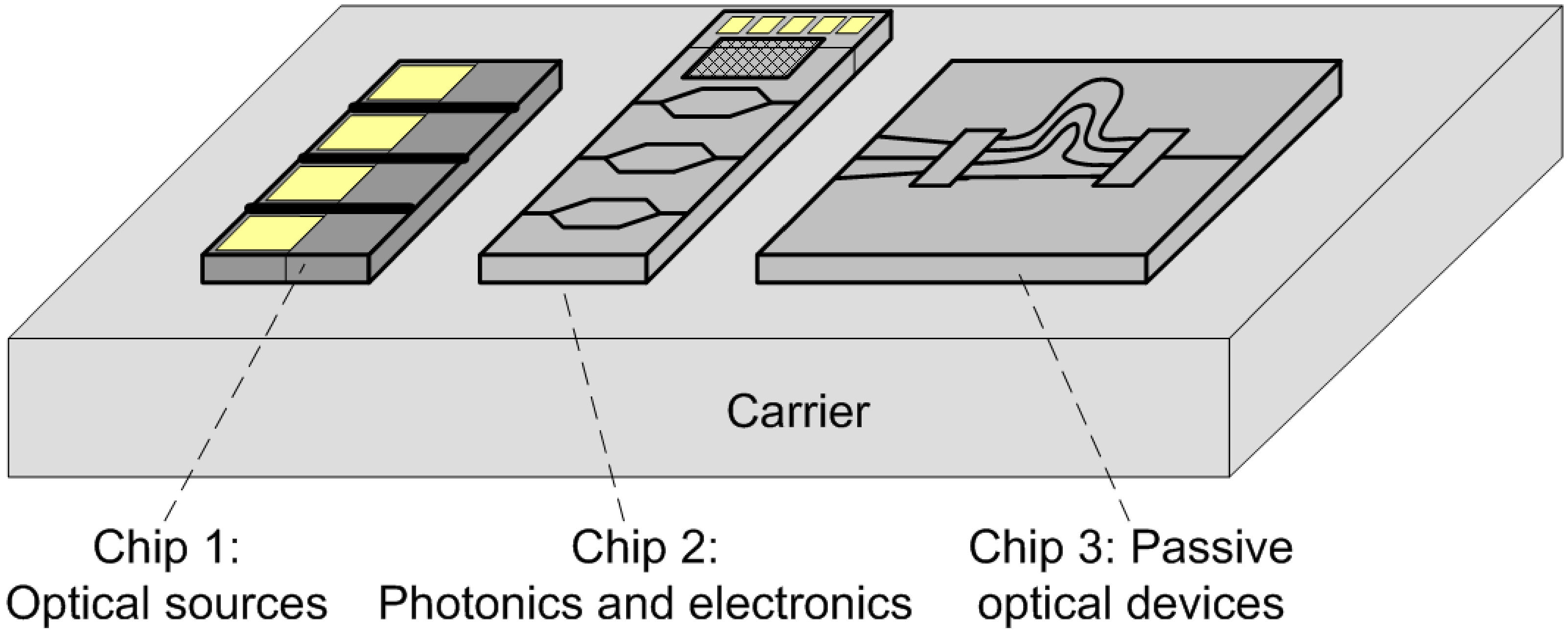
Photonic wire bonding: Replace metallic wire by a 3D freeform polymer waveguide

- No high-precision/active alignment required
- Can connect to arbitrary mode fields
- High interconnect density
- Automated fabrication



Lindenmann *et al.*, Opt. Express **20**, 17667-17677 (2012)
Lindenmann *et al.*, J. Light. Technol. **33**, 755-760 (2015)
Billah *et al.*, Optica **5**, 876-883 (2018)

Photonic wire bonding: The concept



Lindenmann *et al.*, Opt. Express **20**, 17667-17677 (2012)
Lindenmann *et al.*, J. Light. Technol. **33**, 755-760 (2015)
Billah *et al.*, Optica **5**, 876-883(2018)

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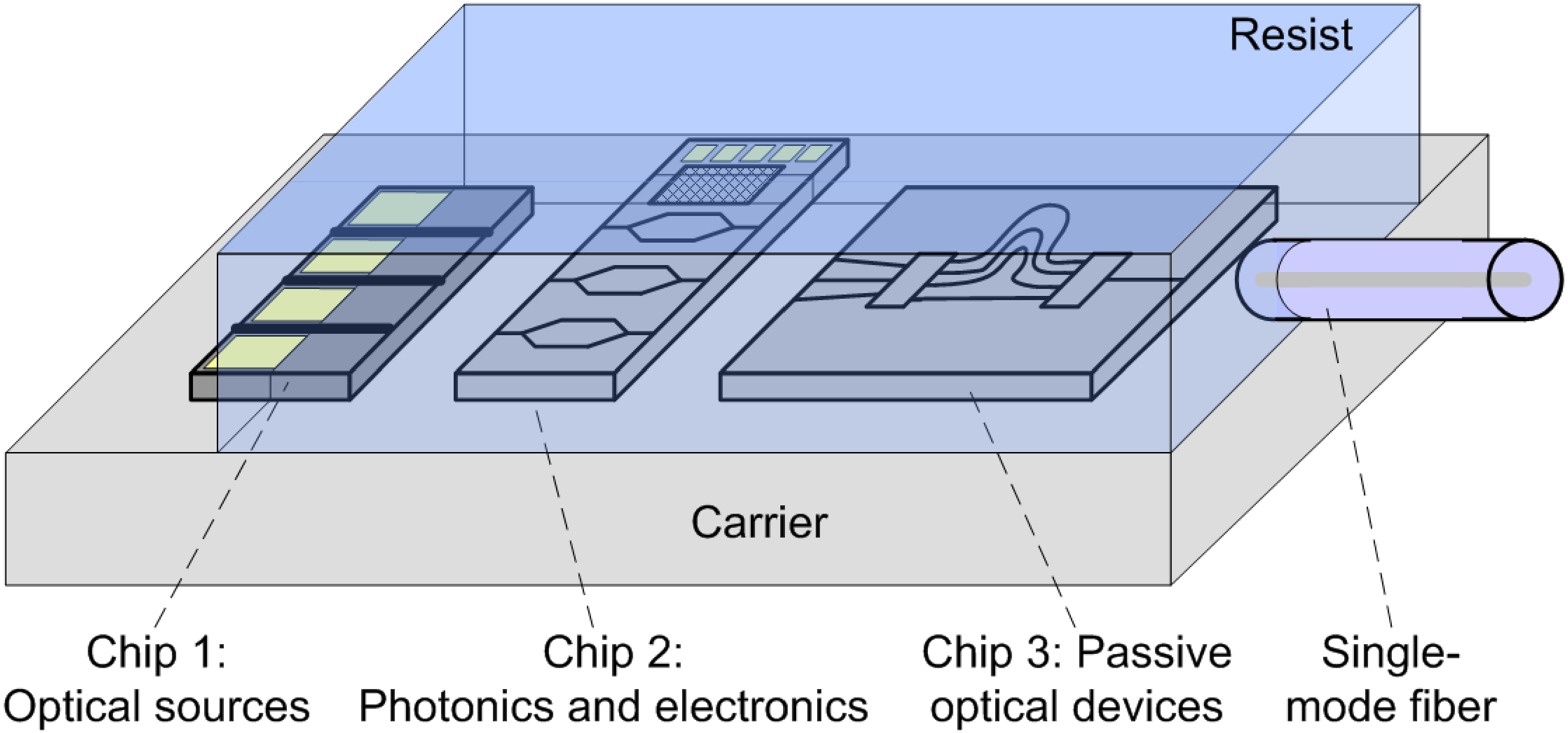

Lindenmann *et al.*, Opt. Express **20**, 17667-17677 (2012)
Lindenmann *et al.*, J. Light. Technol. **33**, 755-760 (2015)
Billah *et al.*, Optica **5**, 876-883(2018)

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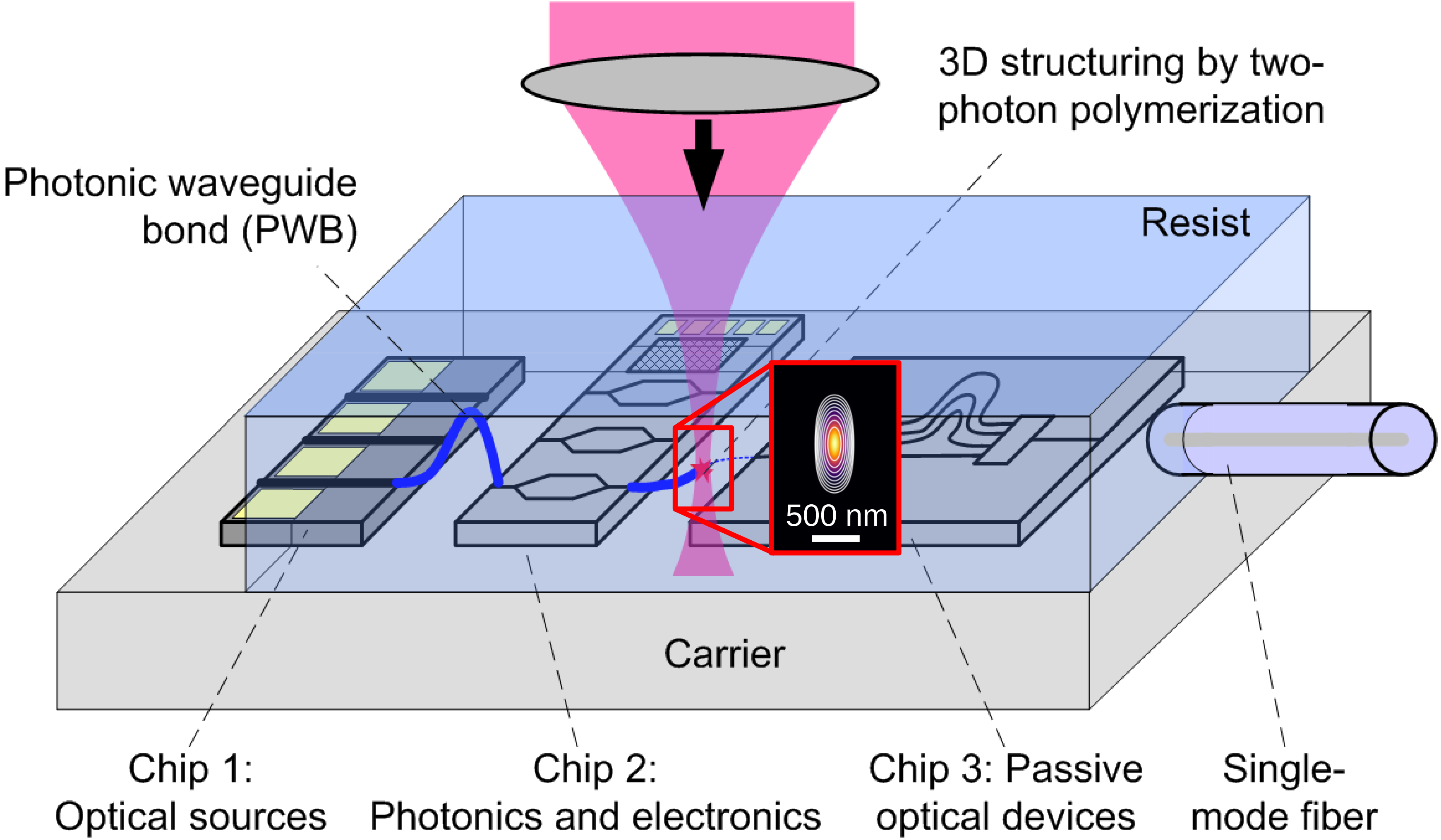
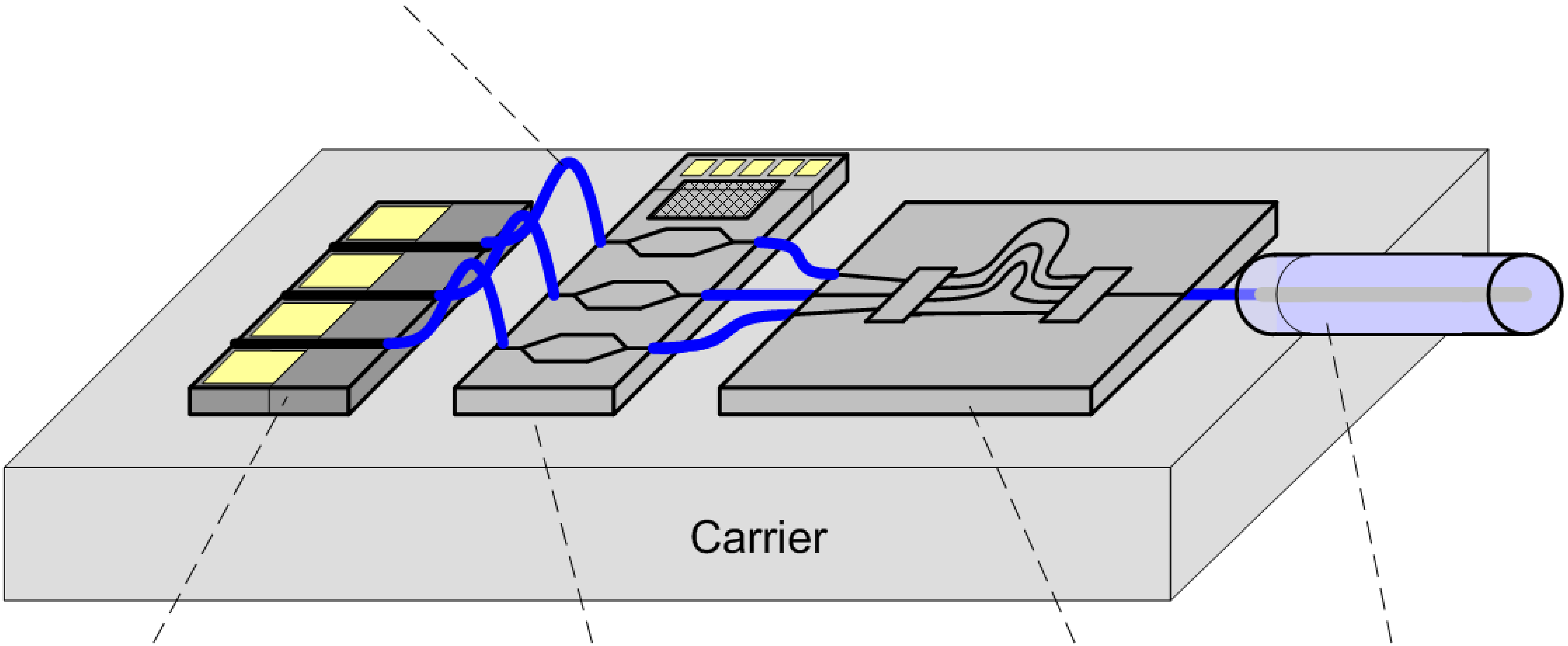


Lindenmann *et al.*, Opt. Express **20**, 17667-17677 (2012)
Lindenmann *et al.*, J. Light. Technol. **33**, 755-760 (2015)
Billah *et al.*, Optica **5**, 876-883(2018)

Photonic wire bonding: The concept

Photonic wire bond (PWB)



Chip 1:
Optical sources

Chip 2:
Photonics and electronics

Chip 3: Passive
optical devices

Single-
mode fiber

Lindenmann *et al.*, Opt. Express **20**, 17667-17677 (2012)
Lindenmann *et al.*, J. Light. Technol. **33**, 755-760 (2015)
Billah *et al.*, Optica **5**, 876-883(2018)

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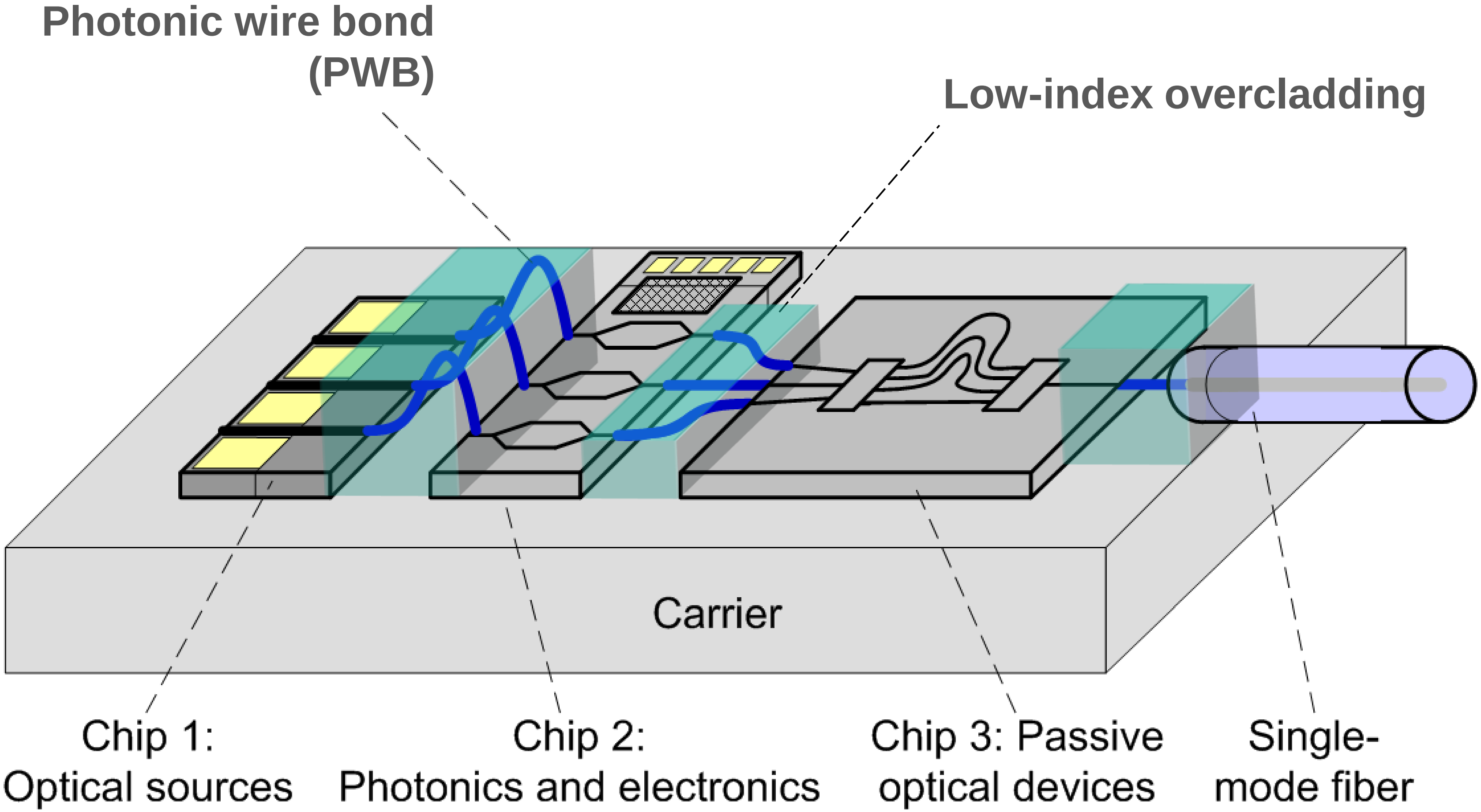
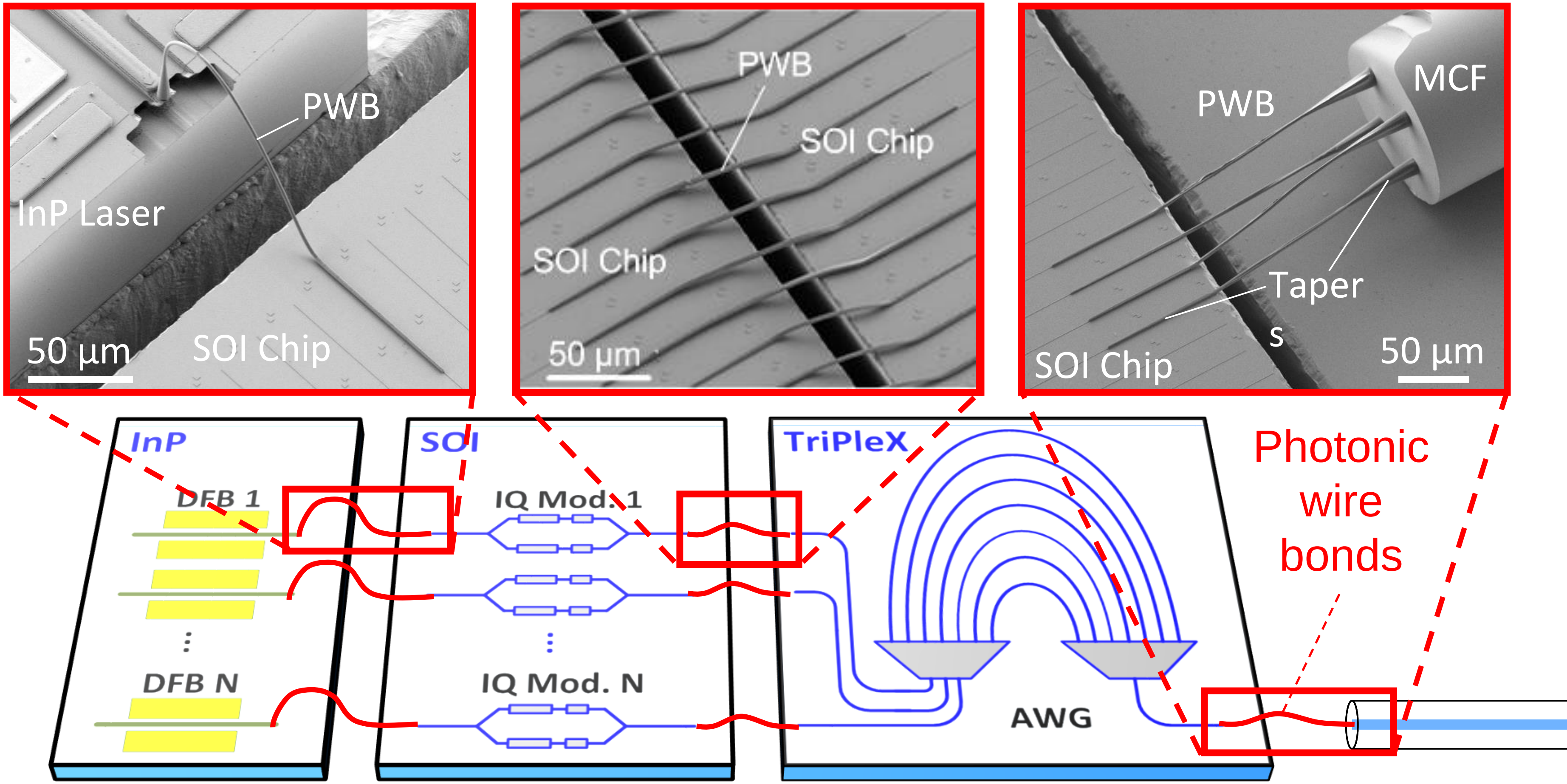


Lindenmann *et al.*, Opt. Express **20**, 17667-17677 (2012)
Lindenmann *et al.*, J. Light. Technol. **33**, 755-760 (2015)
Billah *et al.*, Optica **5**, 876-883(2018)

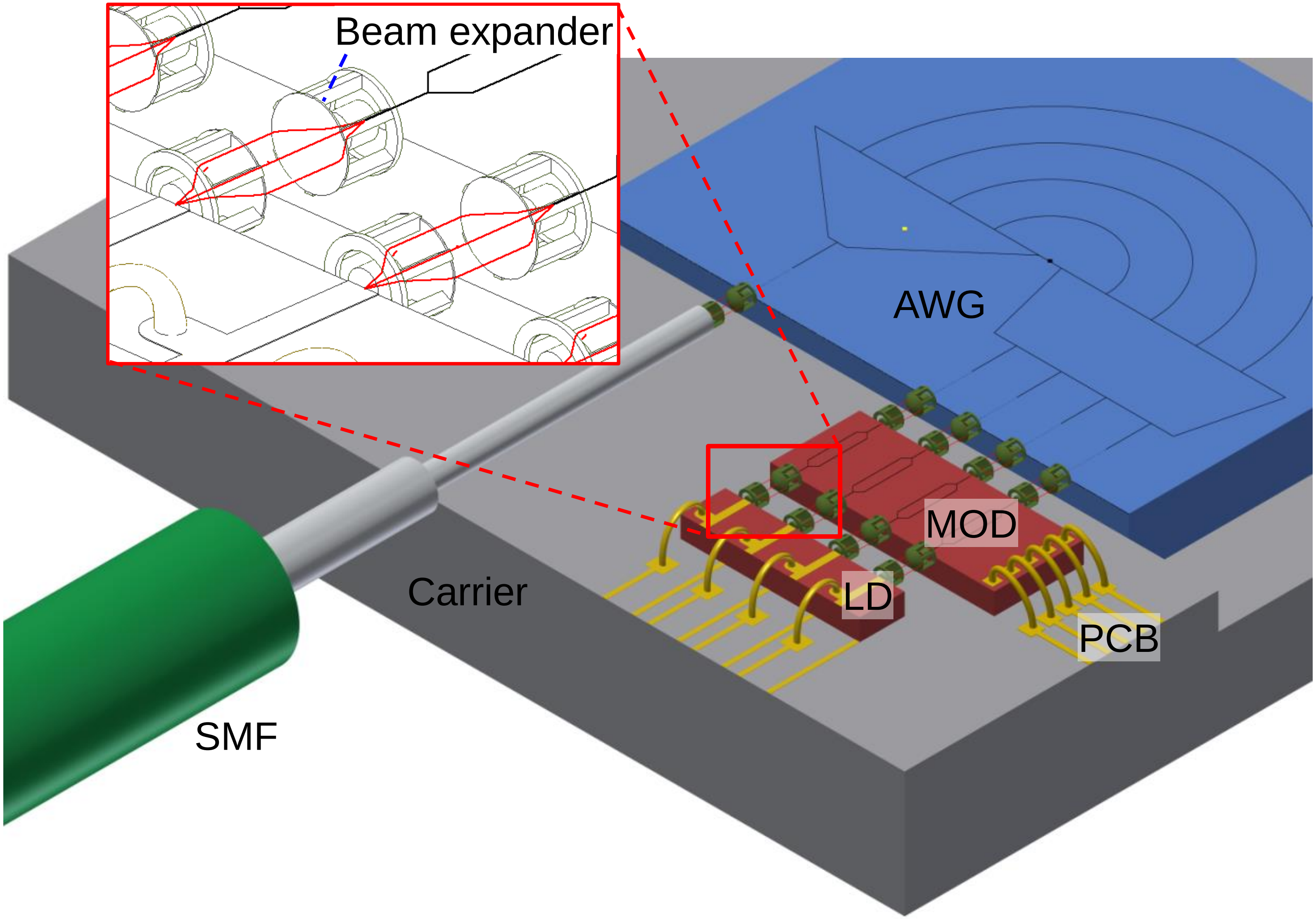
Example: Optical WDM transmitter module



Photonic wire bonds

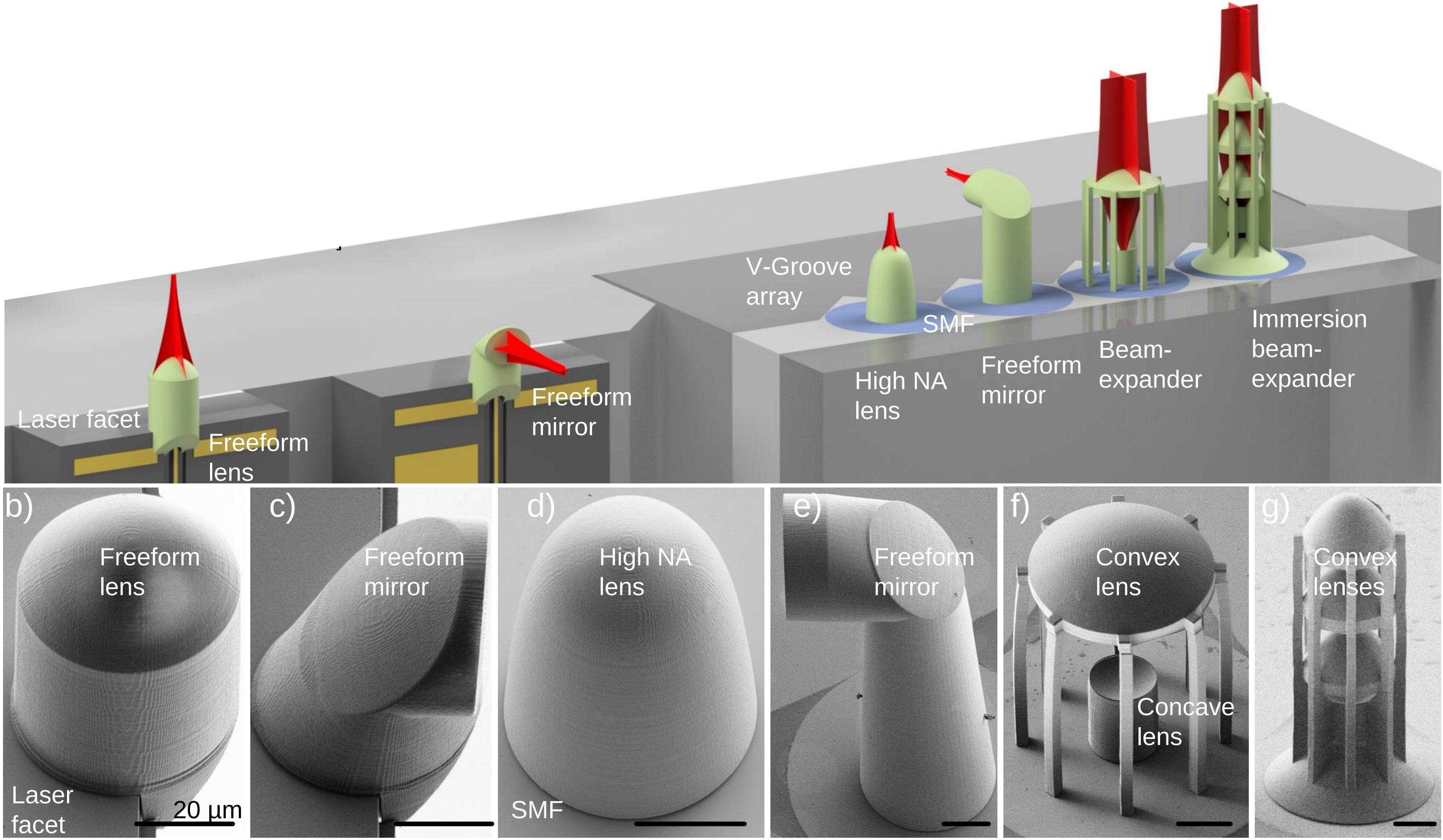
Lindenmann *et al.*, J. Light. Technol. **33**, 755-760 (2015)
Billah *et al.*, Optica **5**, 876-883(2018)

Coupling by facet-attached micro-optical elements



Dietrich *et al.*, Nat. Photon. **12**, 241–247 (2018)

Facet-attached micro-optical elements

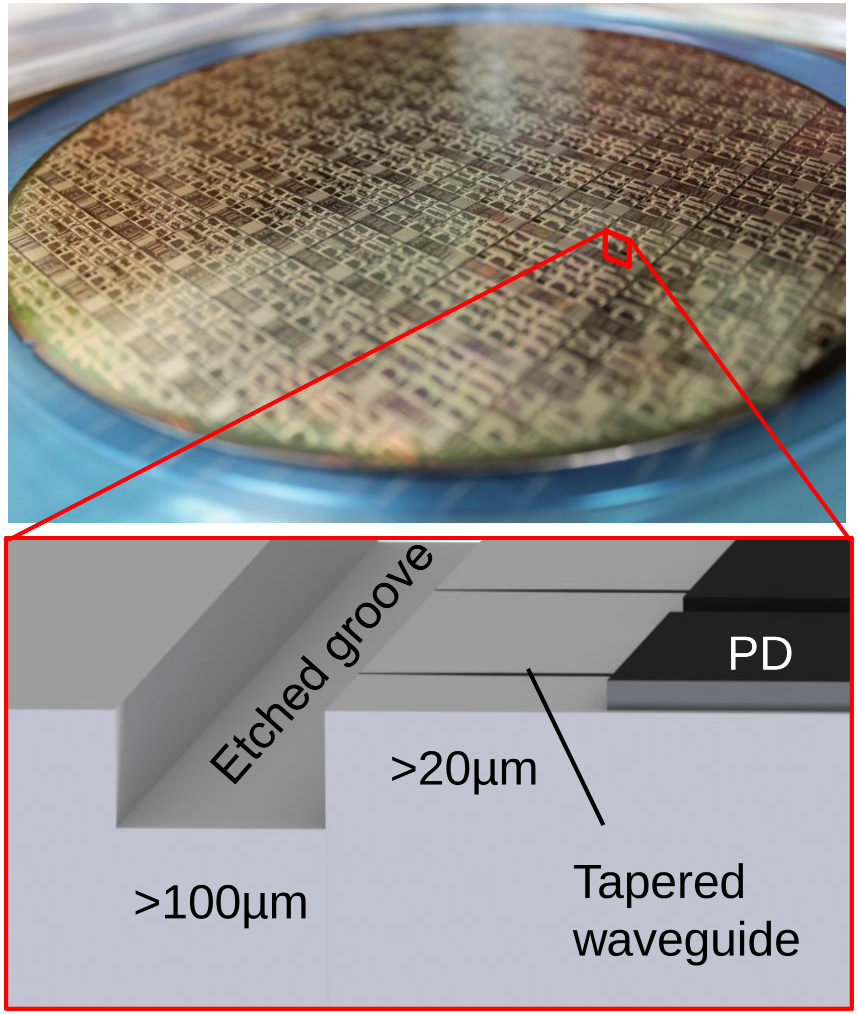


www.vanguard-photonics.com

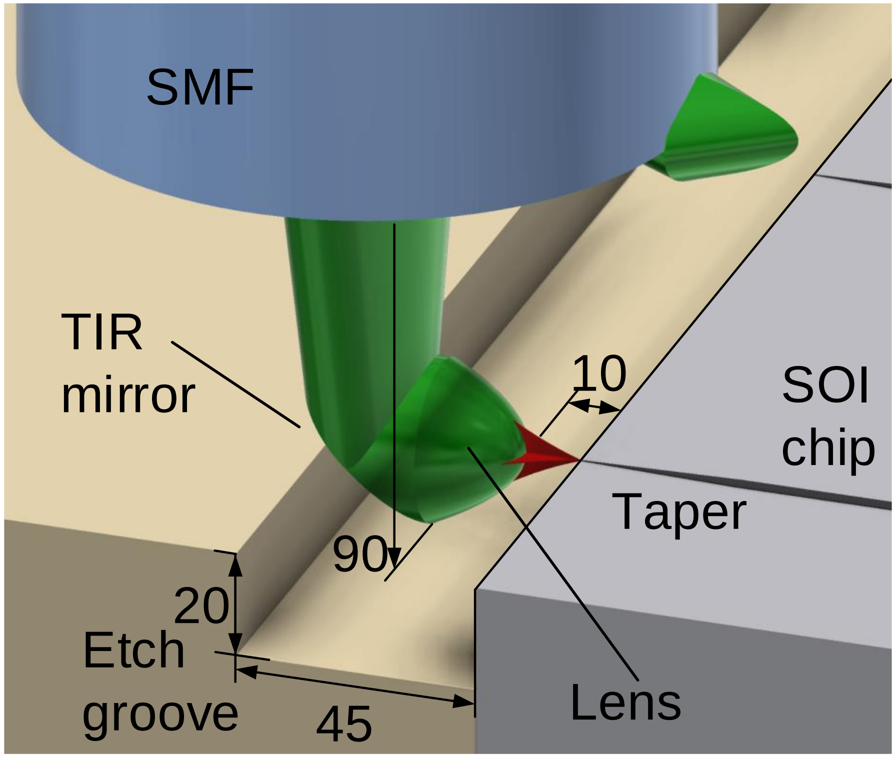
Dietrich *et al.*, Nat. Photon. **12**, 241–247 (2018)

3D-printed micro-optics for wafer-level probing

Challenge: Probing of edge-emitting devices prior to separation



Printing of **3D freeform facet-attaced elements** for wafer-level probing



Reproducibility: ± 0.2 dB

Trappen *et al.*, ECOC 2018, paper Tu4C.2

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- Commercial products and experimental demonstrations
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Summary

Luxtera

Products:

QSFP28 modules

- 100G-PSM4 MSA: 4 x 25 Gbit/s
- Reach up to 2 km

Embedded optical modules

- 2x100G-PSM4 OptoPHY
- Reach up to 2 km

Technology:

- pn-depletion-type Mach-Zehnder modulators
- Standard InP laser diode in silicon micro-package

Intel

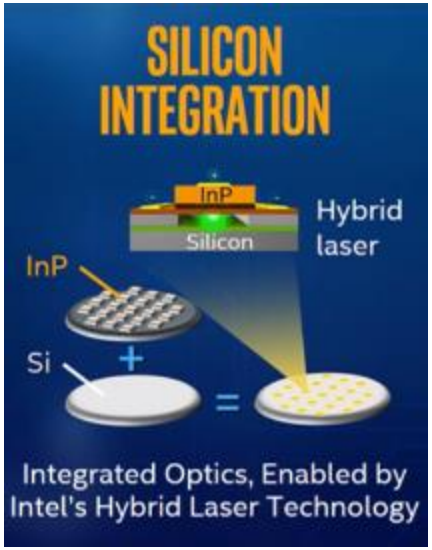
Products: QSFP28 pluggable transceivers

- 100G PSM4
- Reach up to 2 km

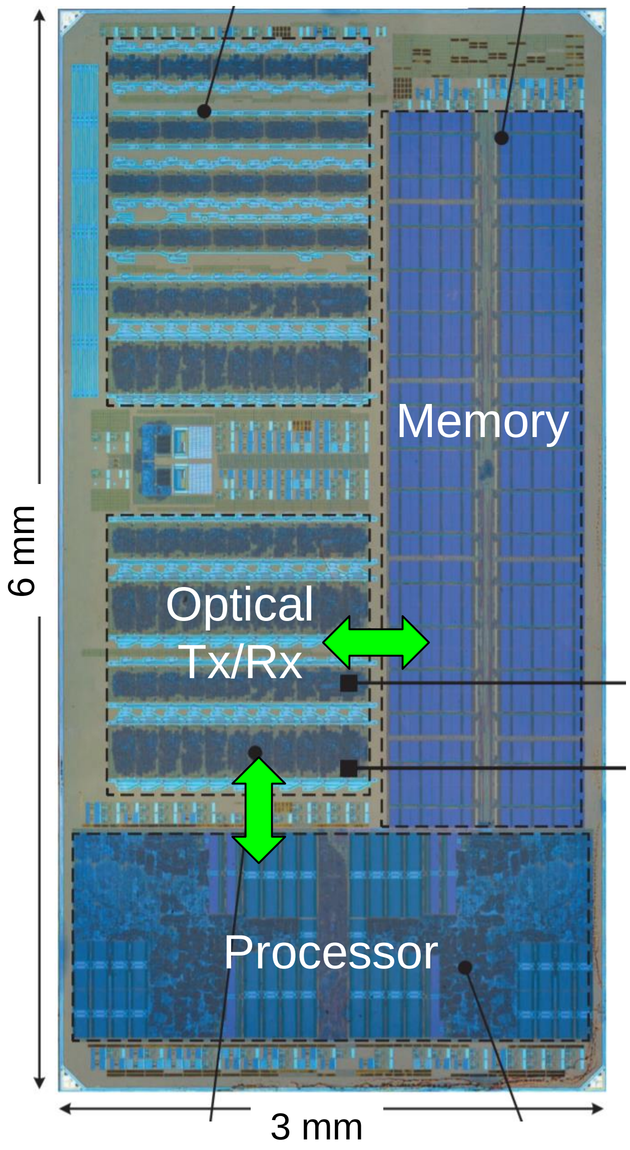
- 100G CWDM4
- Reach up to 10 km
- Data-center and 5G front-hauling

Technology:

- pn-depletion-type Mach-Zehnder modulators
- “Hybrid laser”: Heterogeneous integration of III-V-dies on silicon photonic waveguides

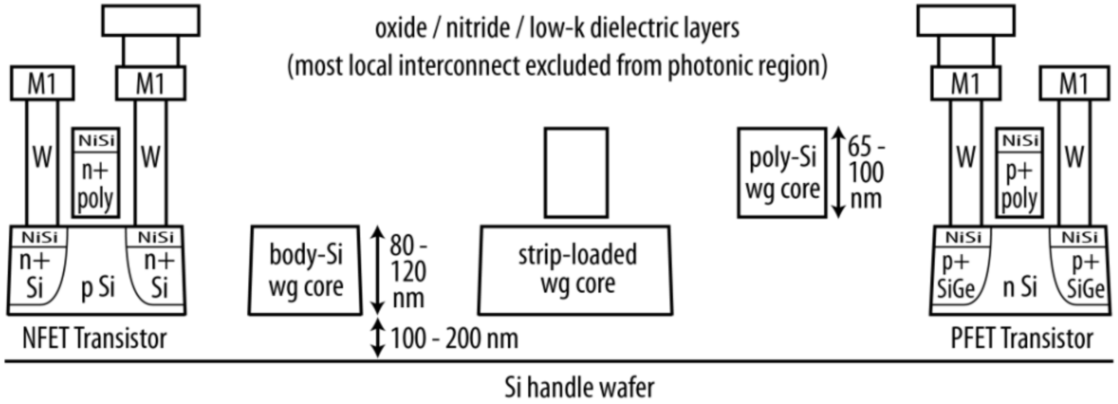


Research demonstration:
Silicon photonic transceivers co-integrated with electronics

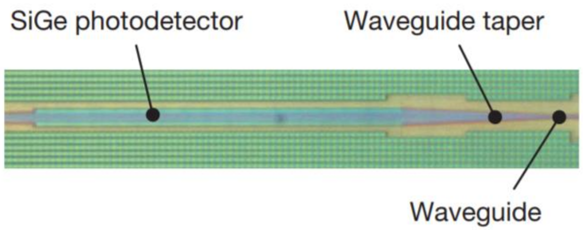


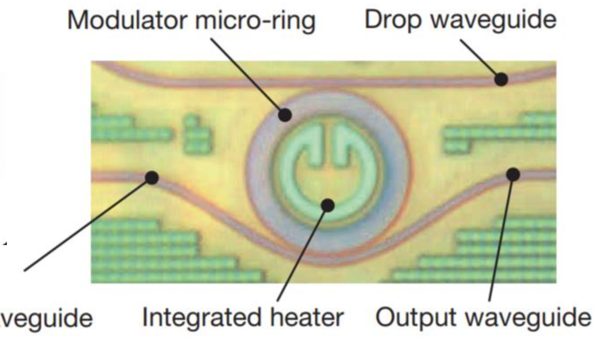
Communication between memory and processor by co-integrated silicon photonic transceivers

- Photonic device fabrication integrated into workflow of commercial 45-nm SOI process without adaptations
- Local removal of substrate to avoid topical leakage



- External laser
- pn-type ring modulator, SiGe photodetector

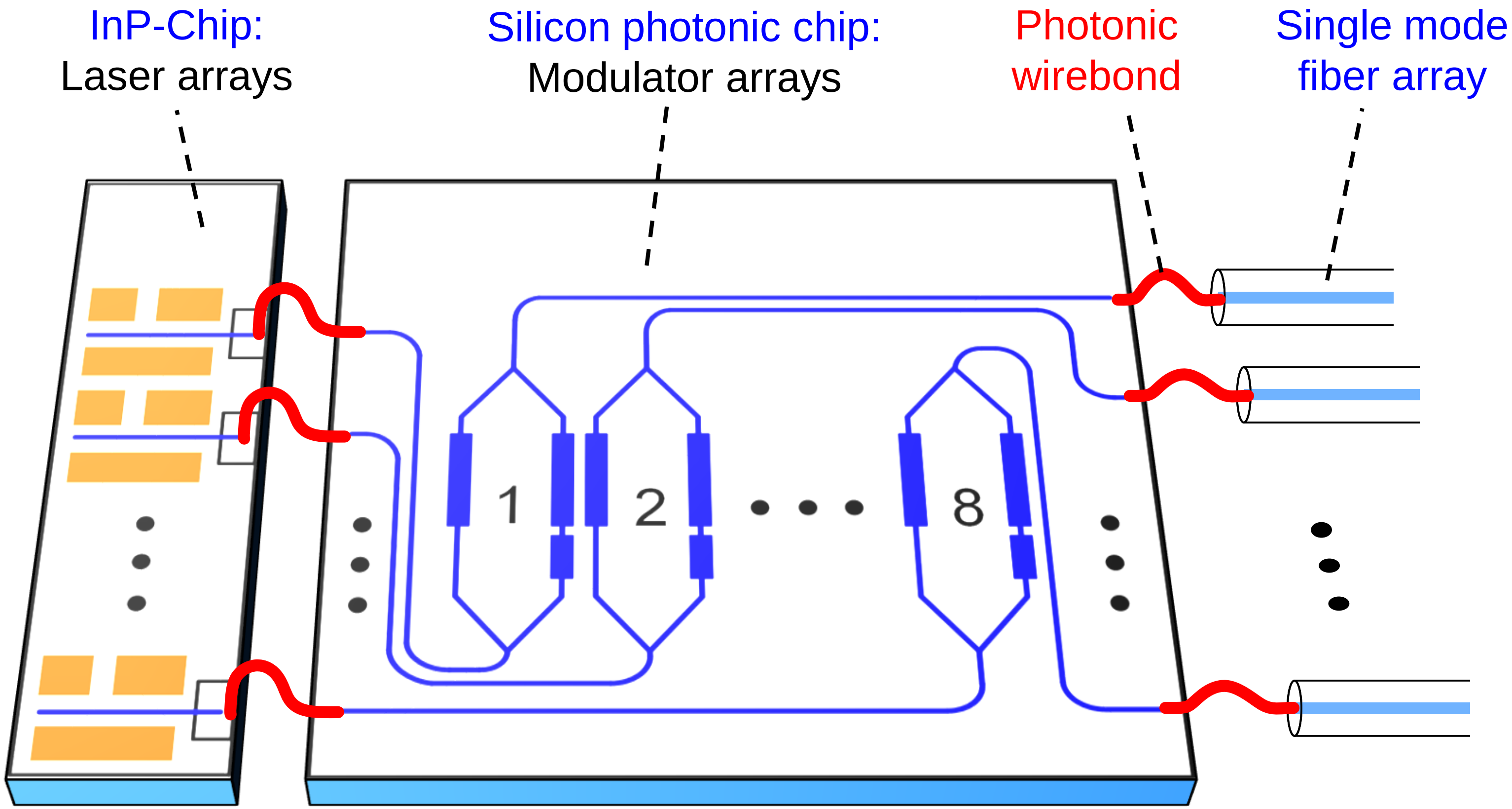




Sun *et al.*, Nature **528**, 534-538 (2015)

Research demonstration: Multi-chip integration transmitter realized by photonic wire bonding

Eight-channel silicon transmitter module



InP-Chip:
Laser arrays

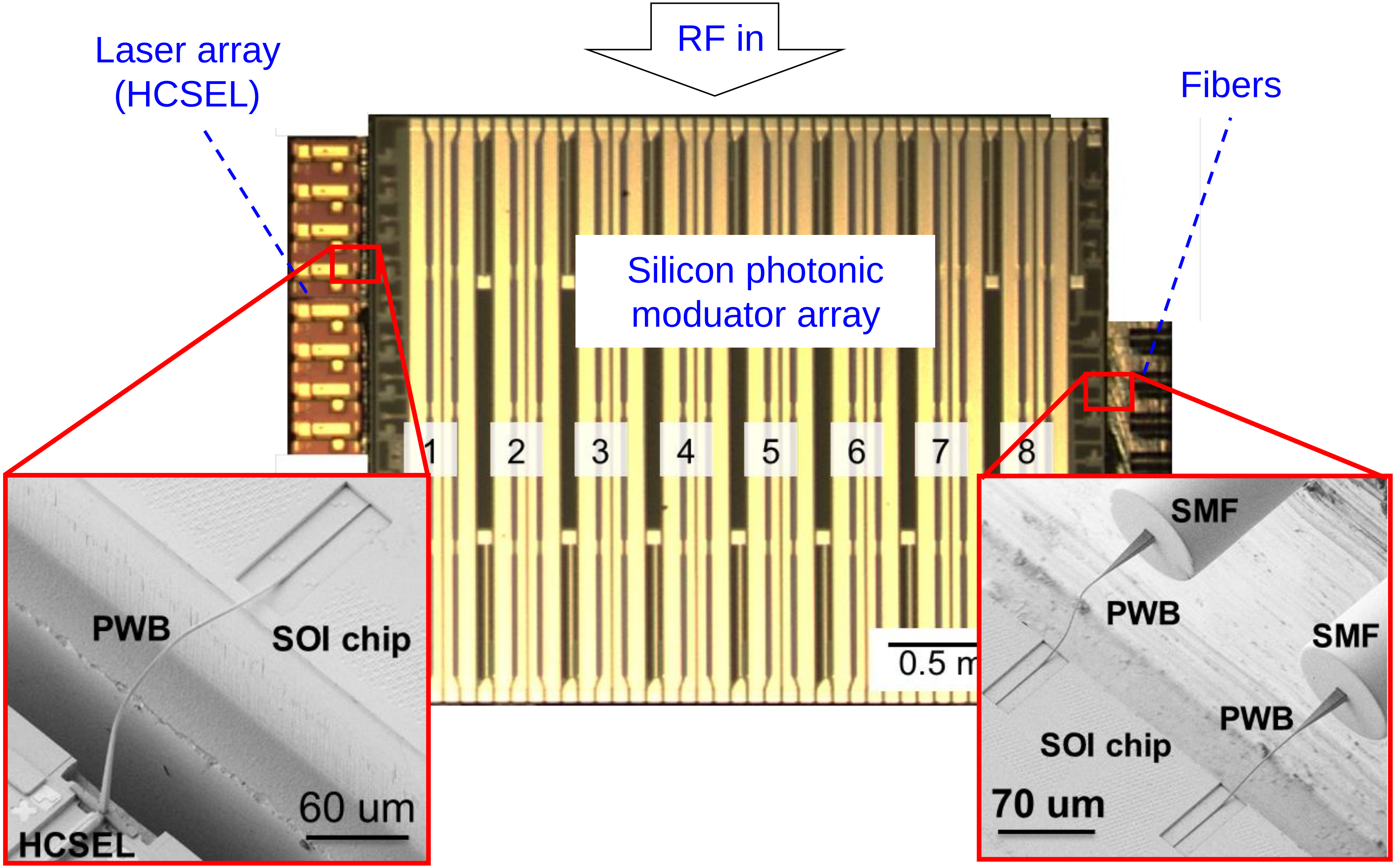
Silicon photonic chip:
Modulator arrays

Photonic
wirebond

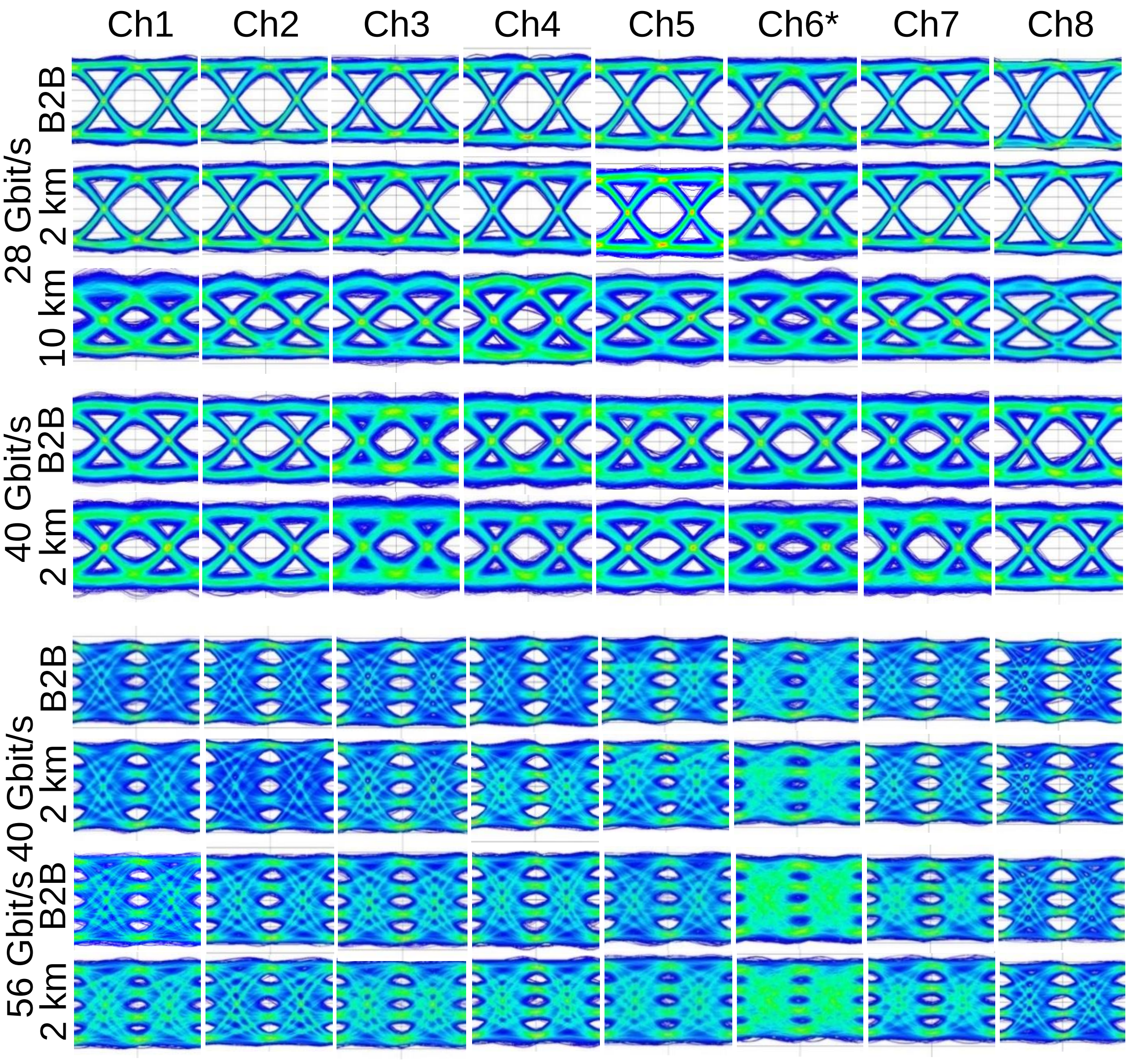
Single mode
fiber array

Billah *et al.*, OFC 2017, Th5D.6. (post-deadline paper)
Billah *et al.*, ECOC 2017, paper Th.PDP.C.1 (post-deadline paper)

Eight-channel silicon photonic transmitter module



Data transmission at up to 448 Gbit/s



28 Gbit/s OOK (line rate 224 Gbit/s) :
Error-free over 2 km
Below HD-FEC limit over 10 km

40 Gbit/s OOK (line rate 320 Gbit/s):
Below HD-FEC limit over 2 km

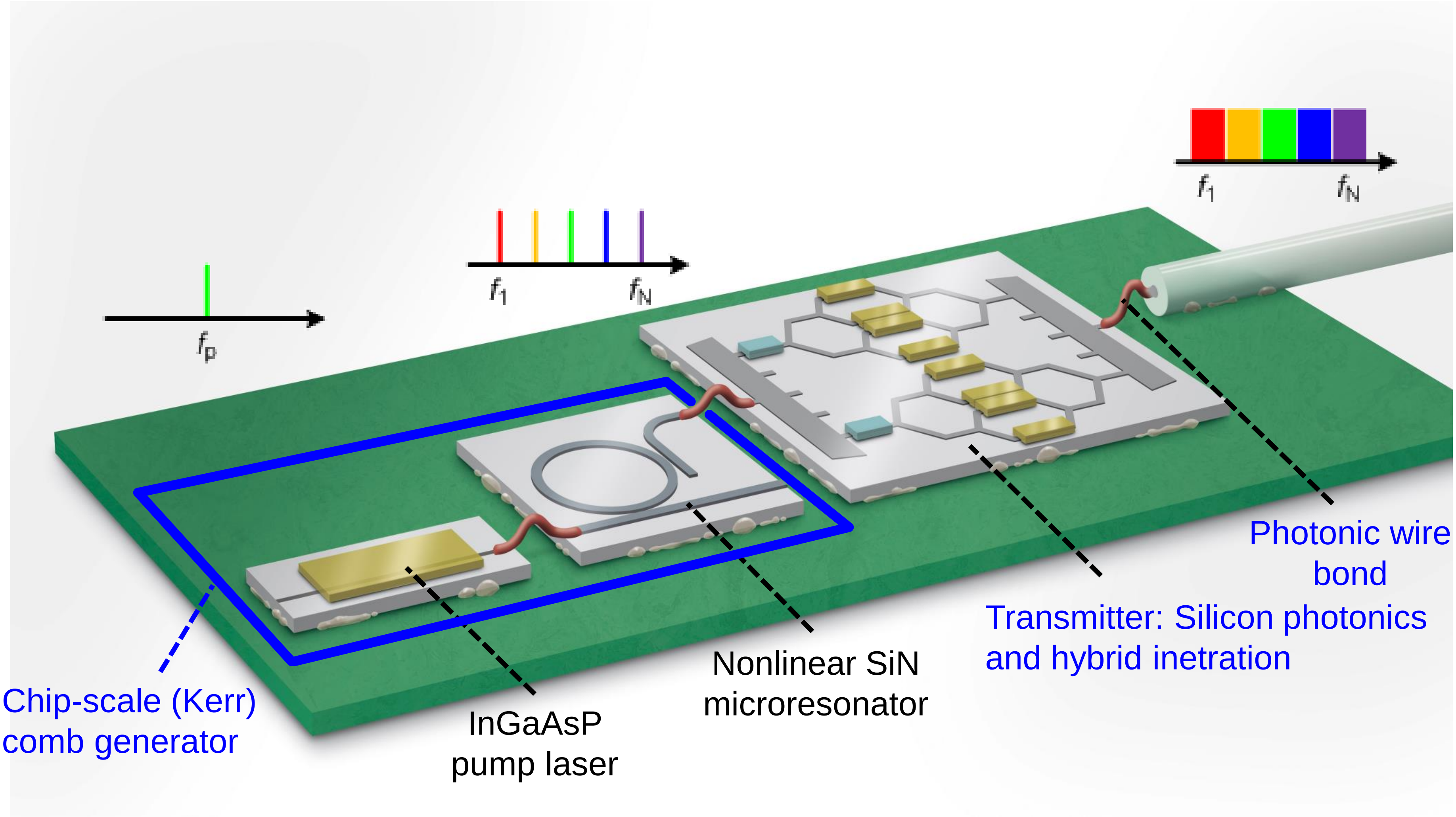
* 3-dB tap!

40 Gbit/s PAM4 (line rate 320 Gbit/s):
Below HD-FEC over for 2 km
(except ch. 6)

56 Gbit/s PAM4 (line rate 448 Gbit/s):
Below HD-FEC limit over 2 km
(except ch. 6)

Billah *et al.*, OFC 2017,
Th5D.6. (post-deadline paper)

Vision: Multi-Tbit/s transceivers using massively parallel WDM



Chip-scale (Kerr) comb generator

InGaAsP pump laser

Nonlinear SiN microresonator

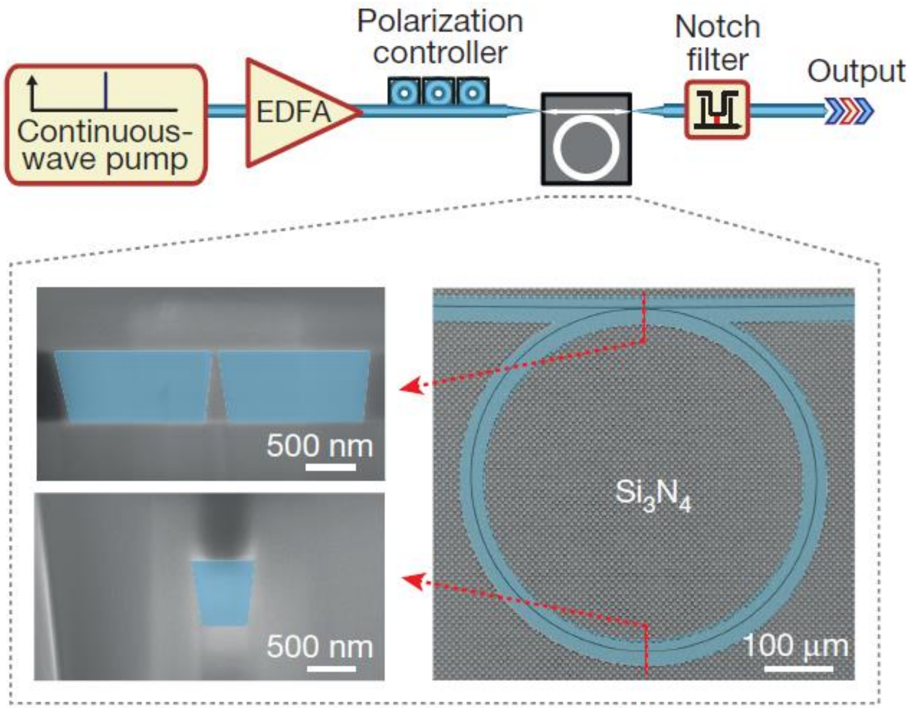
Transmitter: Silicon photonics and hybrid inetration

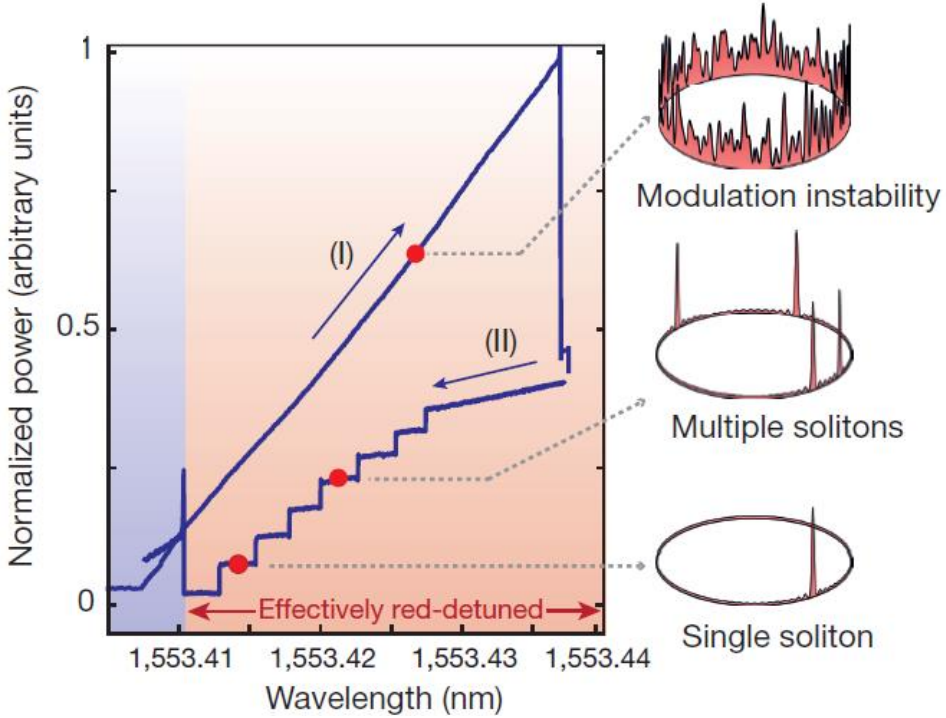
Photonic wire bond

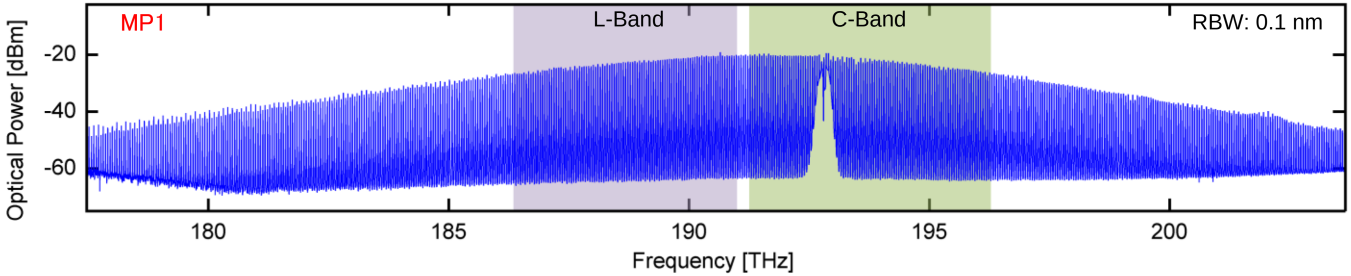
Marin *et al.*, Nature **546**, 274–279 (2017)

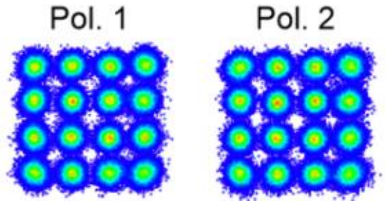
Pfeifle *et al.*, Nat. Photon. **8**, 375 - 380 (2014)

Soliton Kerr comb generation





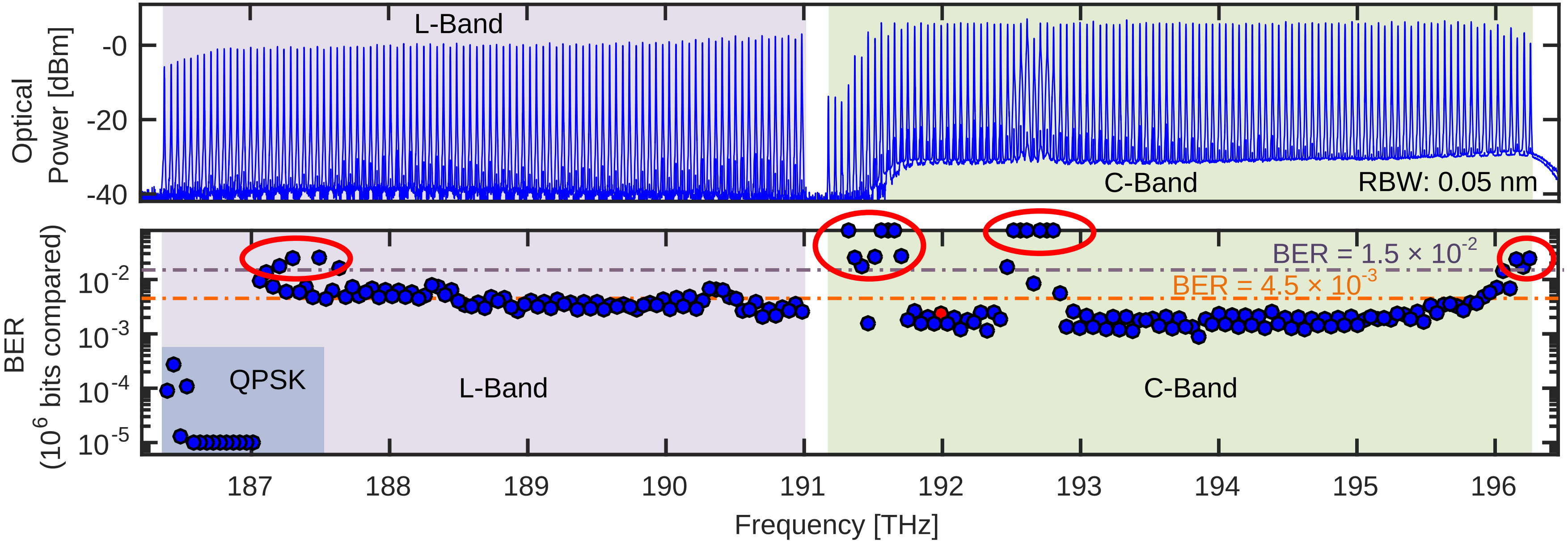




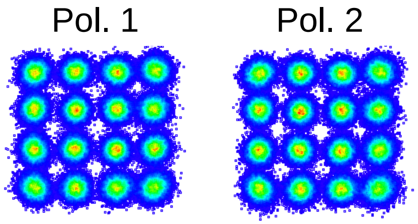
Transmission of > 50 Tbit/s on 179 carriers, derived from a pair of interleaved Kerr combs

Marin *et al.*, Nature **546**, 274–279 (2017)

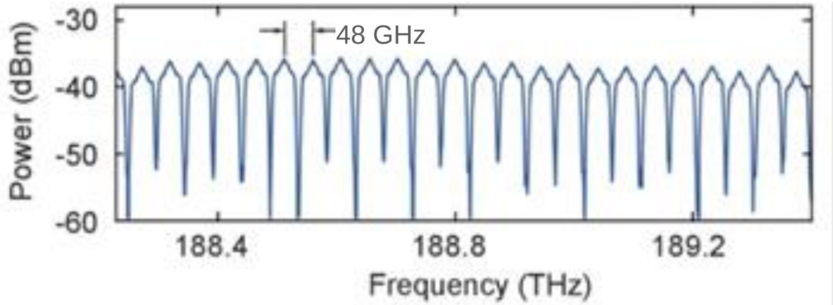
Interleaved soliton combs: Transmission at 50 Tbit/s



- 179 channels within FEC limits:
  165 × 40 GBd PDM-16QAM
  14 × 40 GBd PDM-QPSK
- Line rate (net data rate): 55 Tbit/s (50.2 Tbit/s)
- Impairments by limited amplifier bandwidth saturation power and filter mismatch (avoidable)
- High spectral efficiency: 5.6 bit/s/Hz



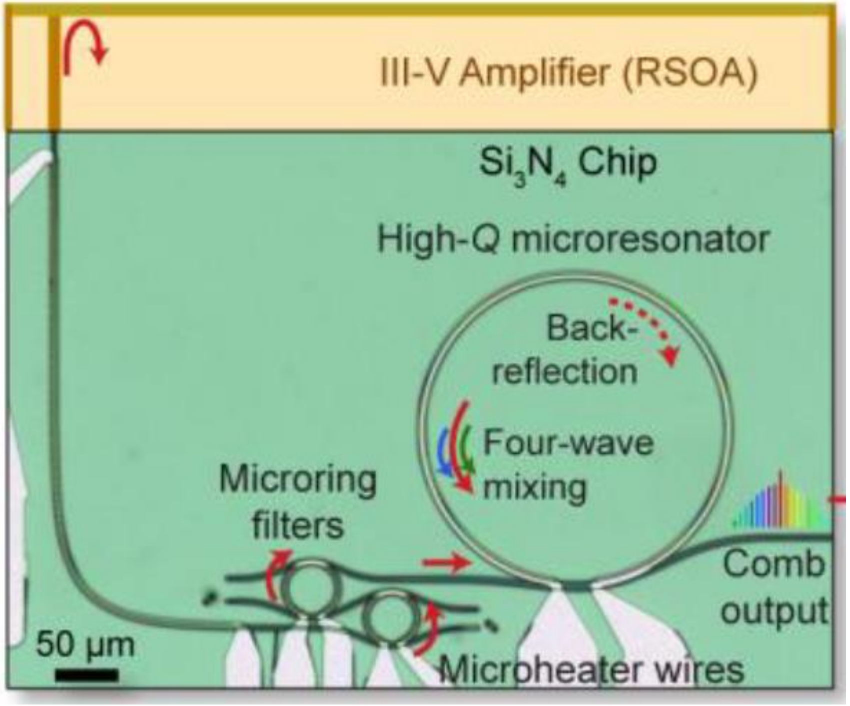
Data channel at 192.0 THz

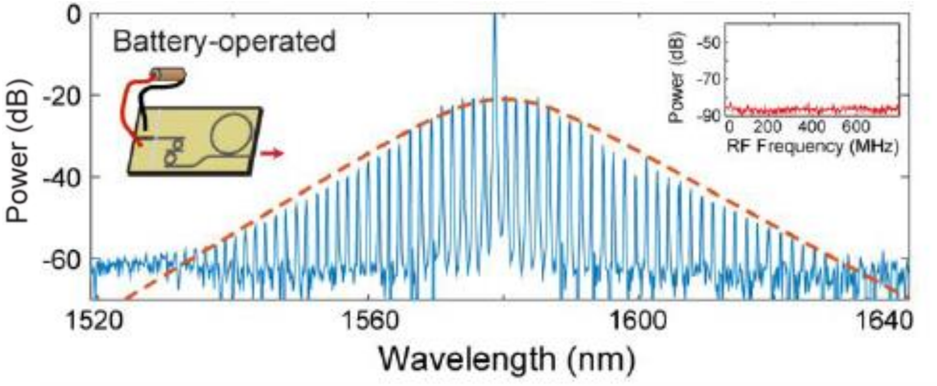


Marin *et al.*, Nature **546**, 274–279 (2017)

Crucial: Low-power operation of soliton Kerr combs

Battery-driven integrated Kerr comb generator operated at ~ 10 mW optical pump power





Intrinsic Q: $(8.0 \pm 0.8) \times 10^6$

Pump wavelength aligned to resonance by narrowband back-reflection from Rayleigh scattering in microresonator

Challenge: Optical output power and power conversion efficiency (still) insufficient for data transmission in massively parallel silicon photonic circuits

Stern *et al.*, *Nature* **562**, 401–405 (2018)

Other examples of low-power Kerr comb sources:

- Suh *et al.*, arXiv:1901.08126 (2019)
- Liu *et al.*, Optica **5,** 1347-1353 (2018)
- Yang *et al.,* Nature Photonics **12**, 297 (2018)
- Raja *et al.*, Nature Communications **10**, 680 (2019)

Silicon Photonics, Hybrid Integration, and Frequency Combs: Technologies for High-Bandwidth Communications

Introduction

- Scalability challenges in optical communications
- Silicon photonics and the need for hybrid integration

Silicon-based building blocks for high-bandwidth transceivers

- Waveguides and passive devices
- Photodetectors
- Light sources
- Modulators

Packaging and system assembly

- Coupling interfaces to silicon photonic waveguides
- In-situ waveguide fabrication by 3D laser lithography

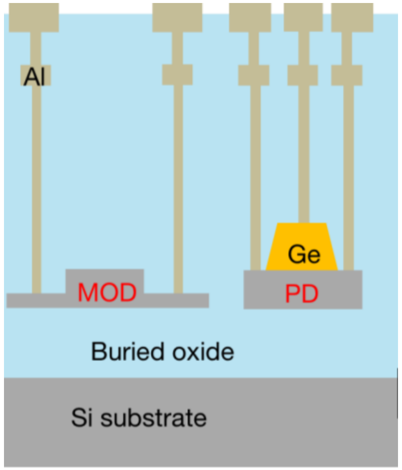
Silicon photonic transceivers

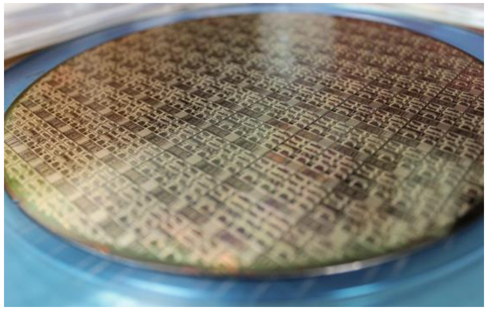
- Commercial products and experimental demonstrations
- Towards massively parallel WDM transceivers

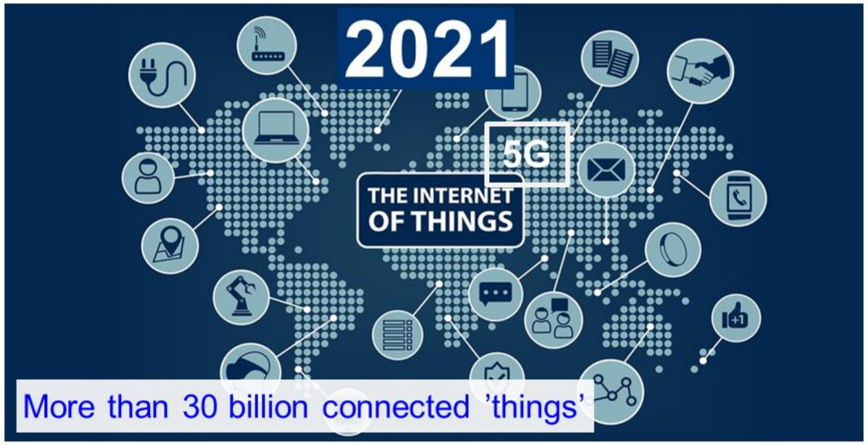
Summary

Summary

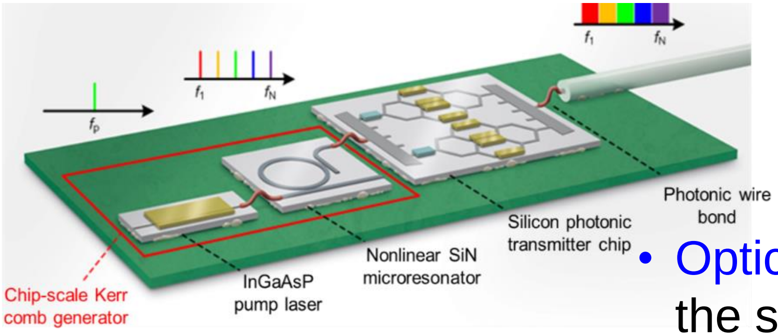
- Future networks will rely on massively parallel data transmission.

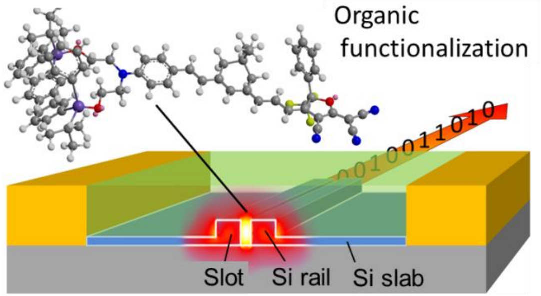


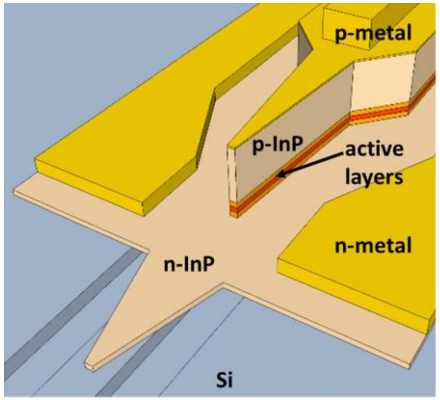




- Silicon photonics is a powerful platform, offering cost-efficient mass production of photonic circuitry at high yield.
- Deficiencies of silicon as an optical material can be overcome by hybrid integration on a chip and package level







- Optical frequency combs might be key to fully exploit the scalability of the silicon photonic platform.