III-V-on-Si Transceivers Based on Micro-Transfer-Printing

Jing Zhang

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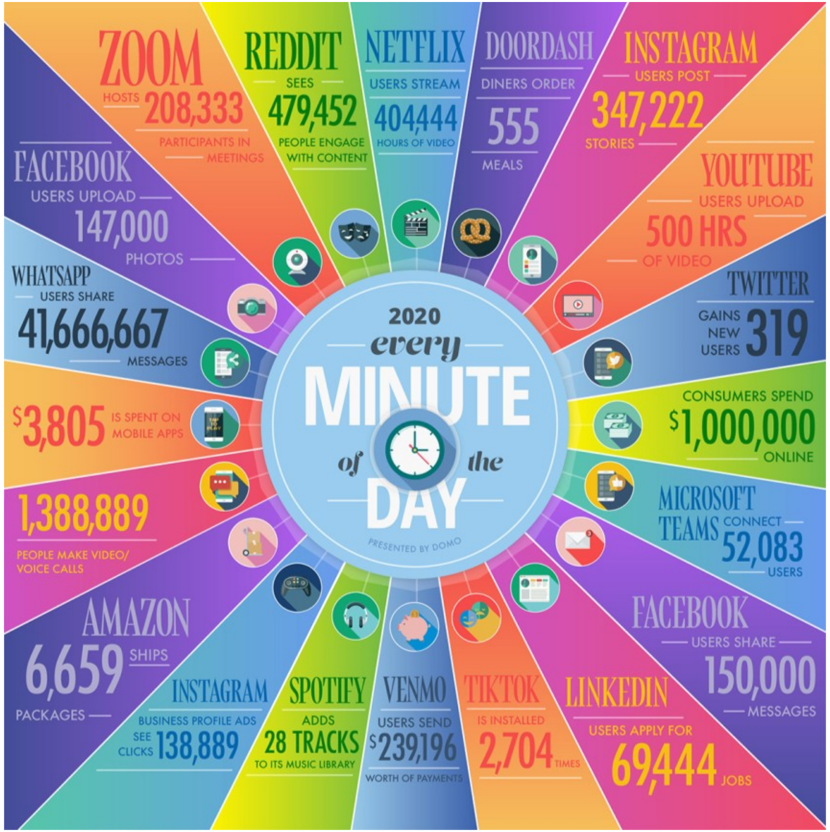
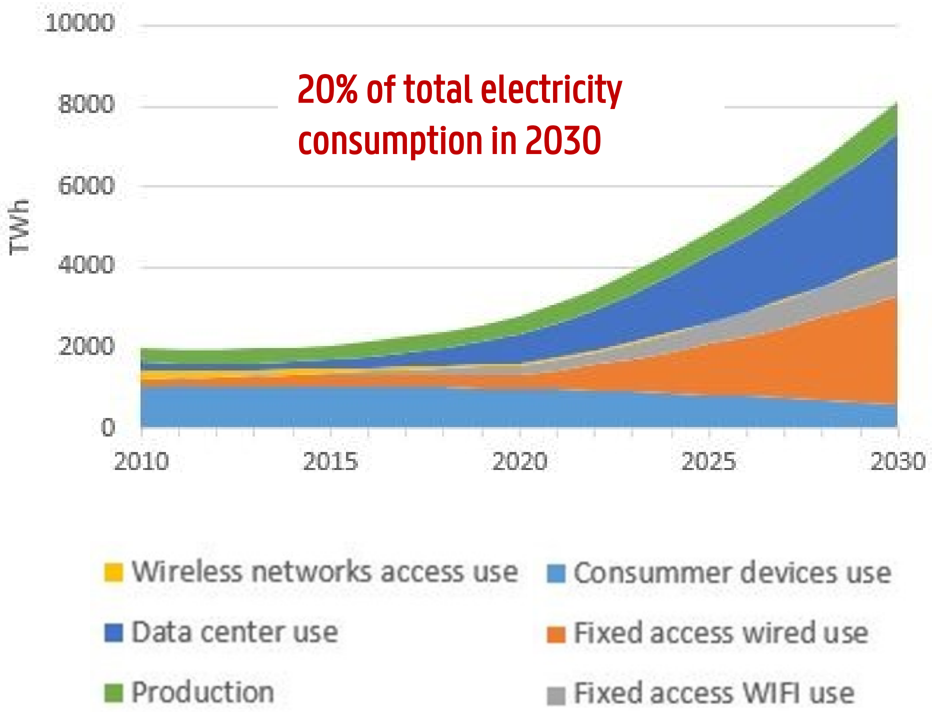
embracing a better life

THE EXPLOSION OF SOCIAL MEDIA





Source: Andrae

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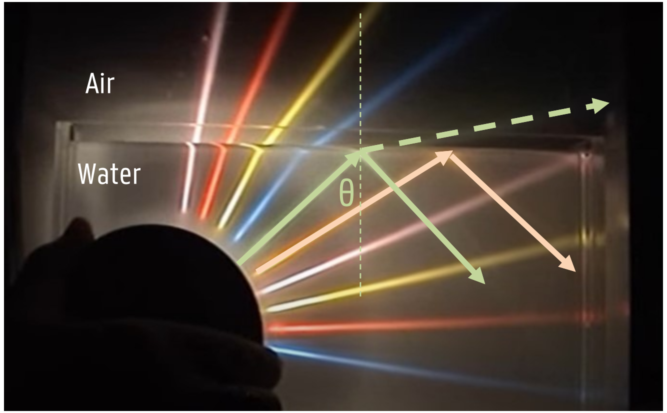
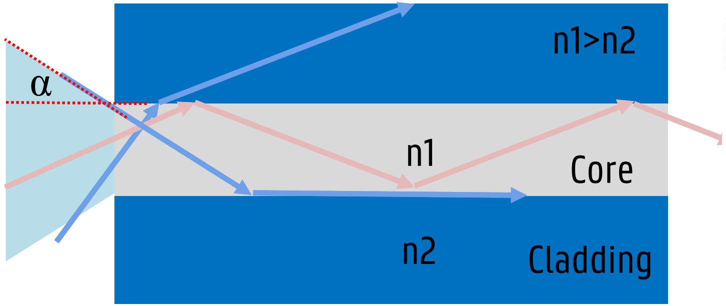
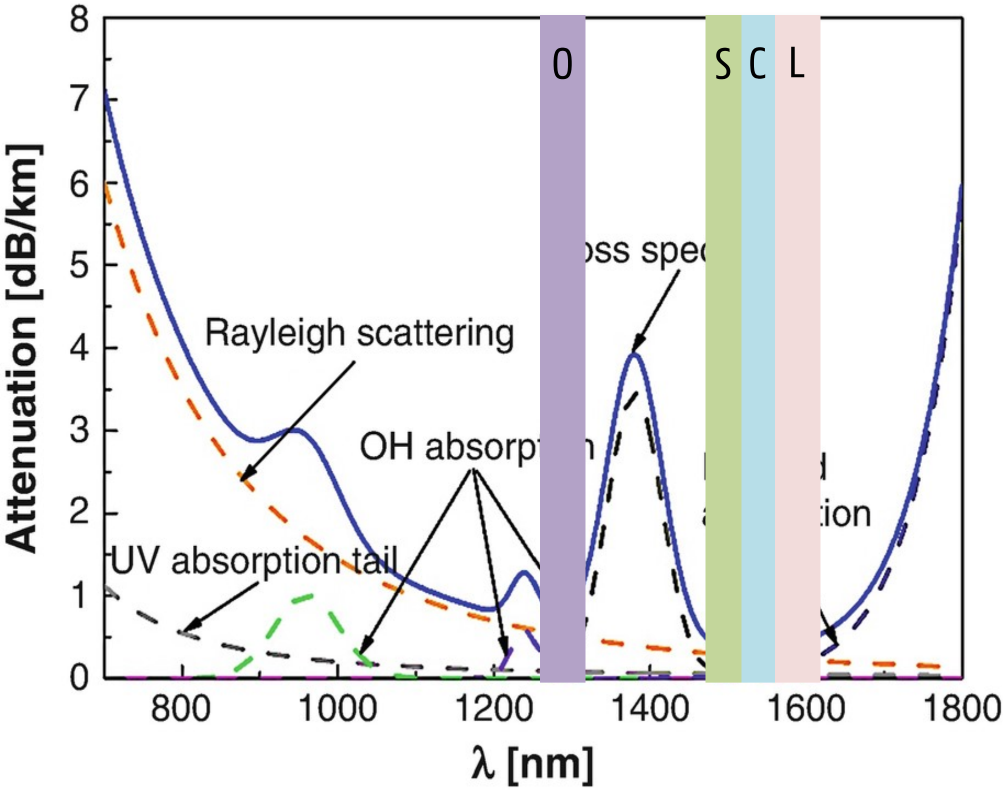
KEY ENABLER: OPTICAL FIBERS



https://www.youtube.com/watch?v=2kBOqfSOnmE

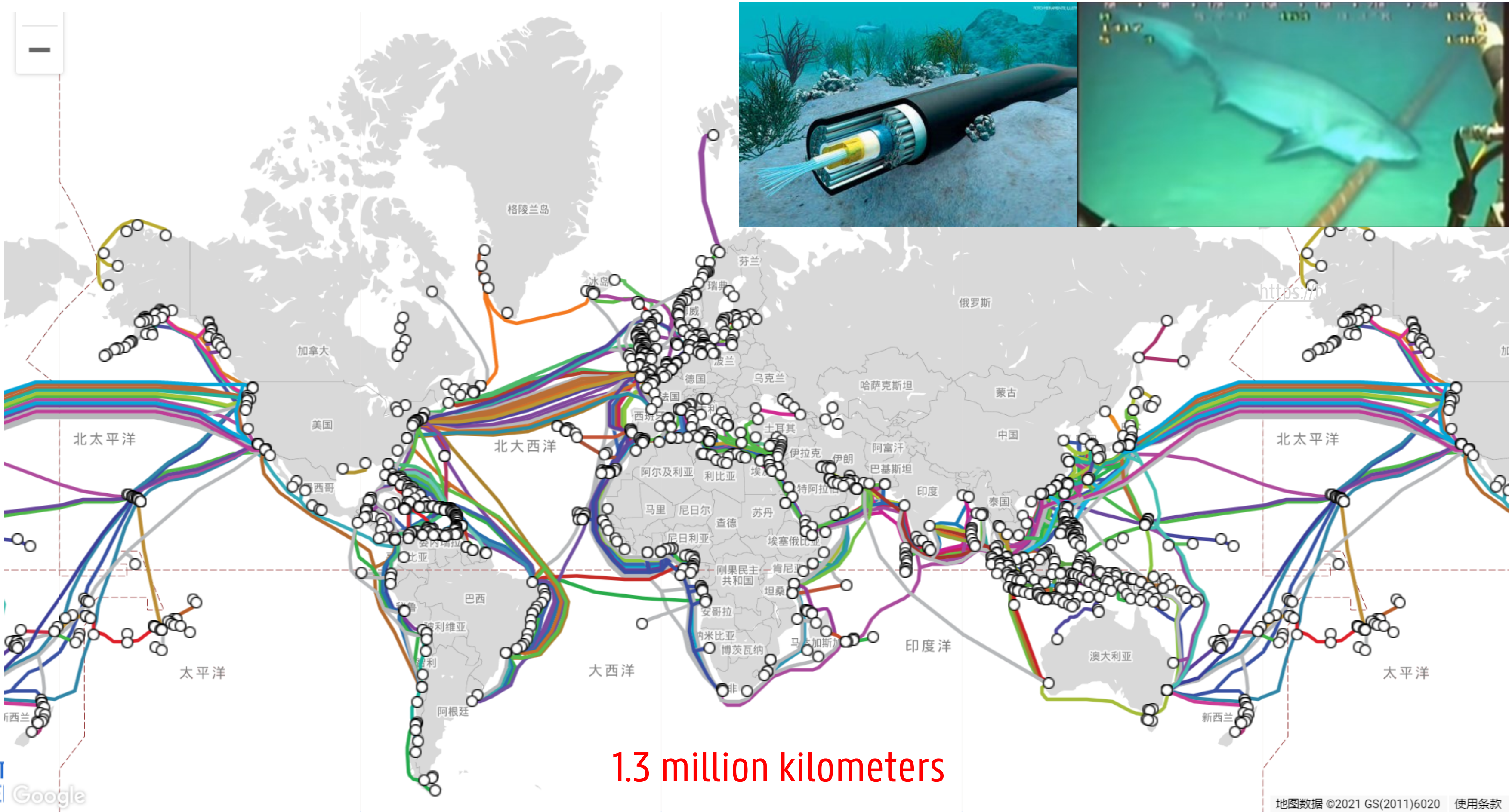




Source:technicasa

M. Ding,et al.,'Handbook of Optical fibers,' pp 1-39 (2018)

Connect the world



1.3 million kilometers

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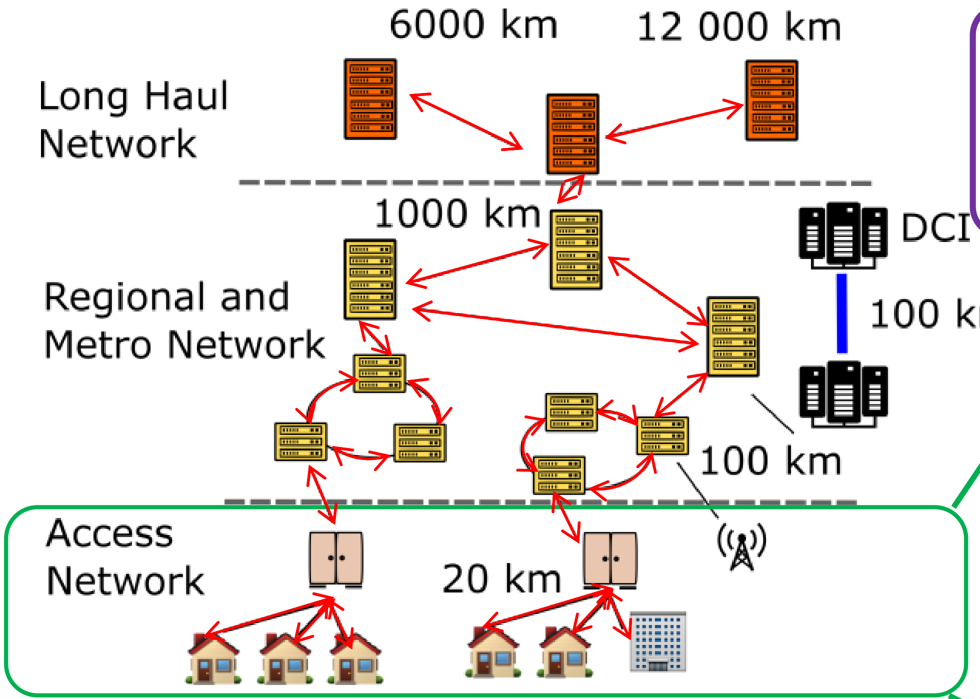
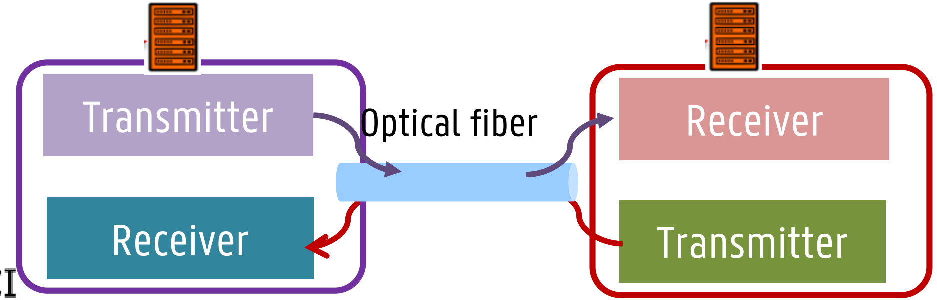
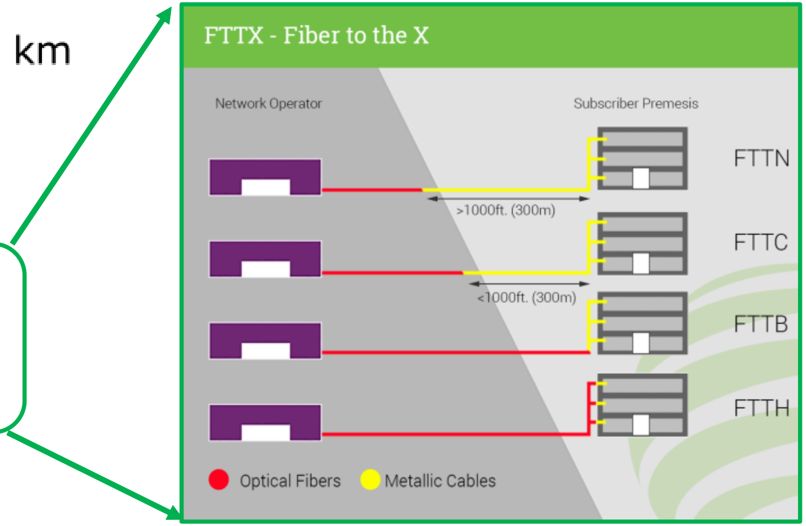
OPTICAL NETWORKS





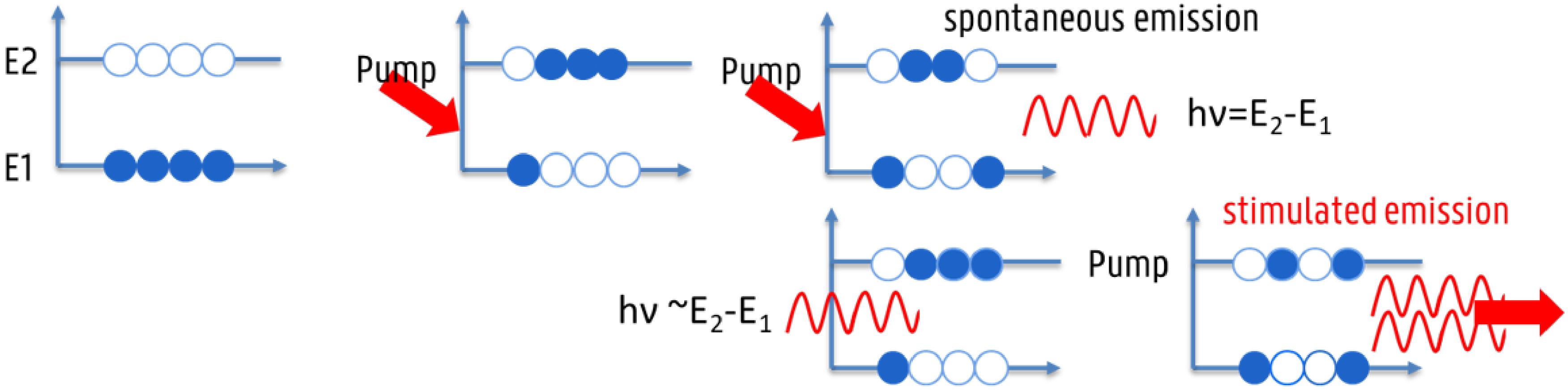


Antonin Gallet, Ph.D thesis 2019.

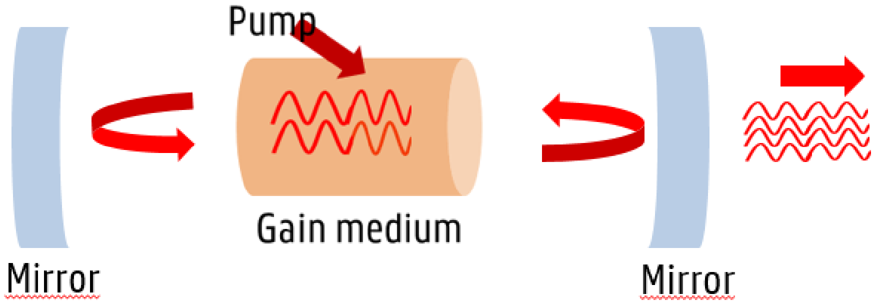
Source:carritech

OPTICAL SOURCE

LASER: Light Amplification by Stimulated Emission of Radiation



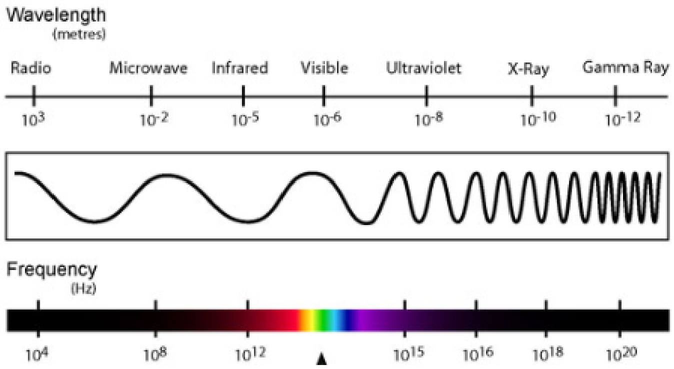
1. Gain medium
2. Pump
3. Cavity



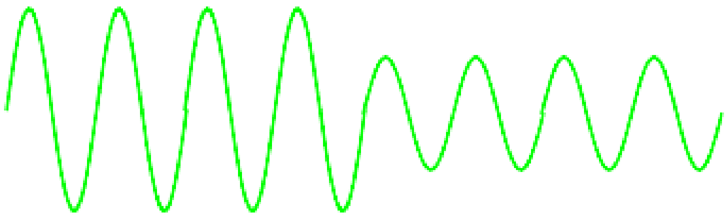
1. Monochromatic
2. Coherent
3. Directional

Properties of light

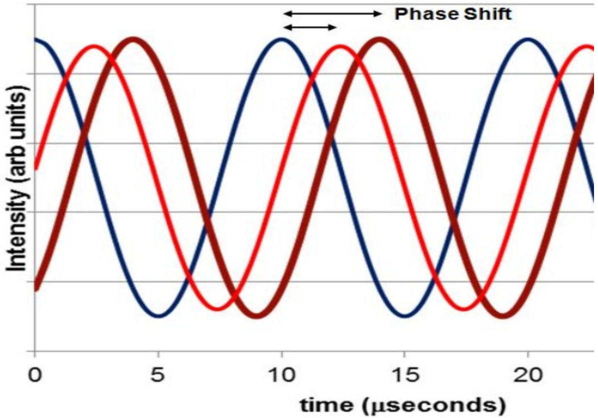
Wavelength(frequency)



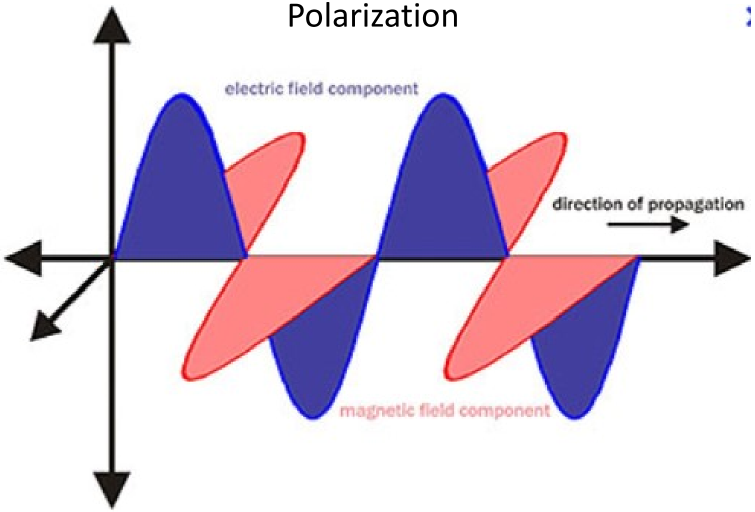
Amplitude (Intensity)



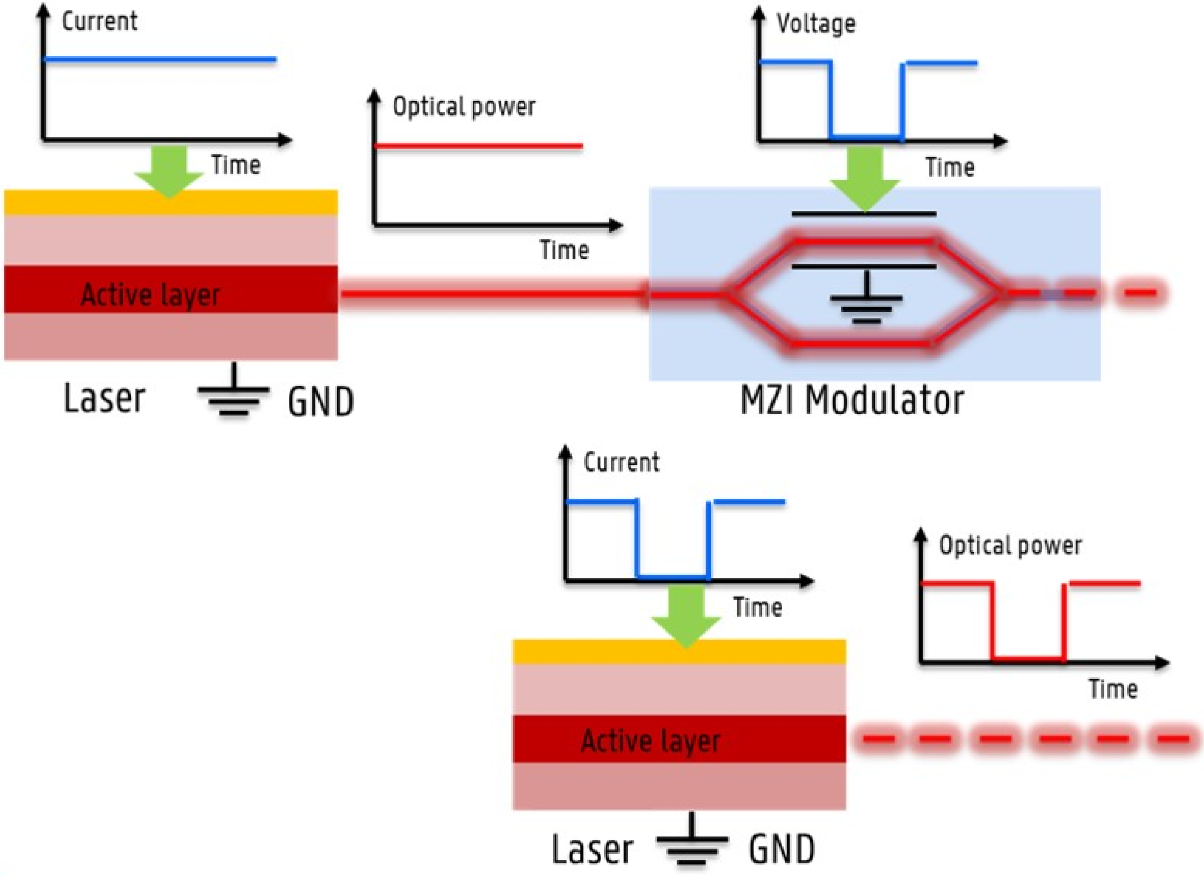
Phase



Polarization



OPTICAL TRANSMITTER



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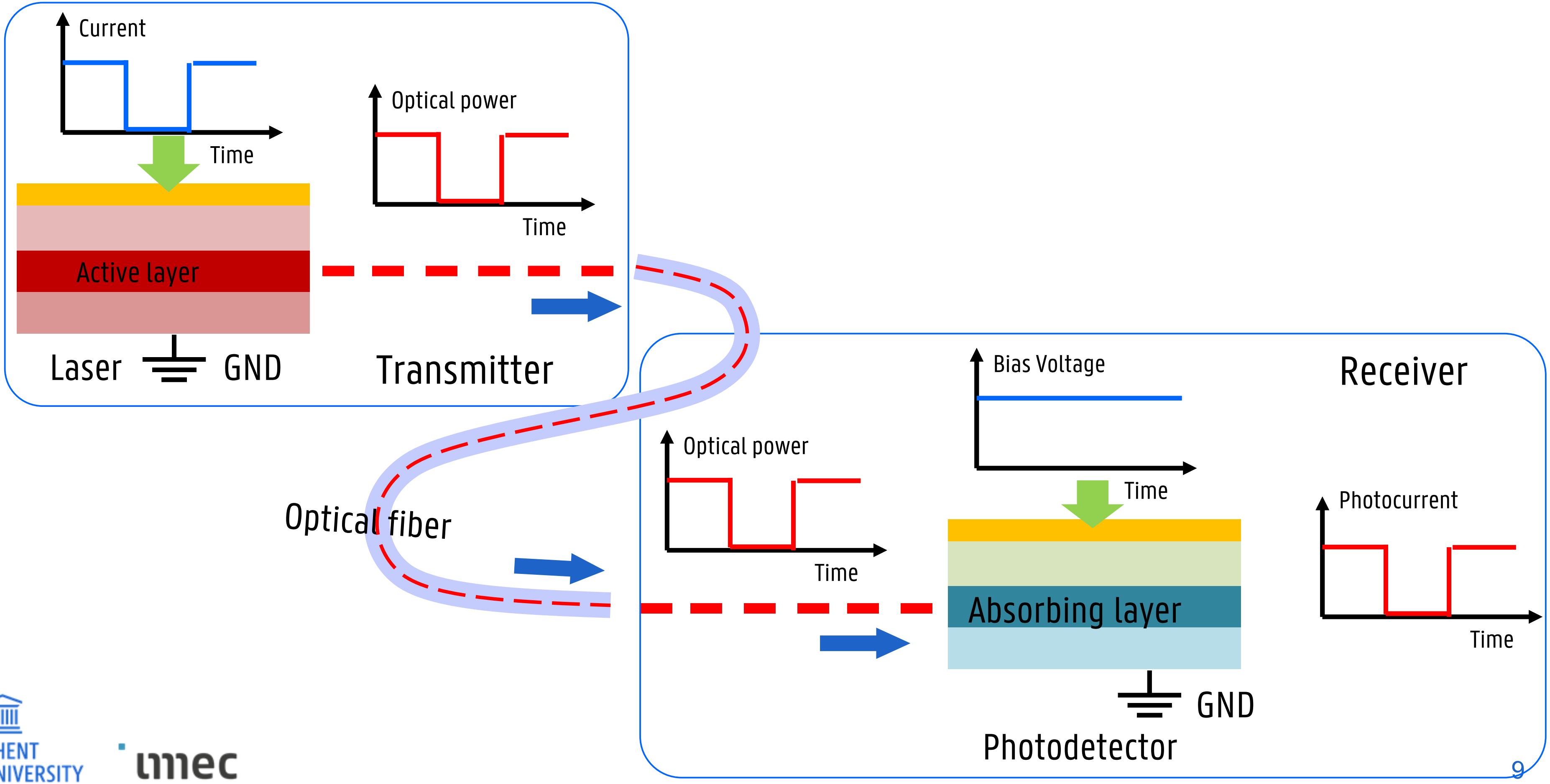
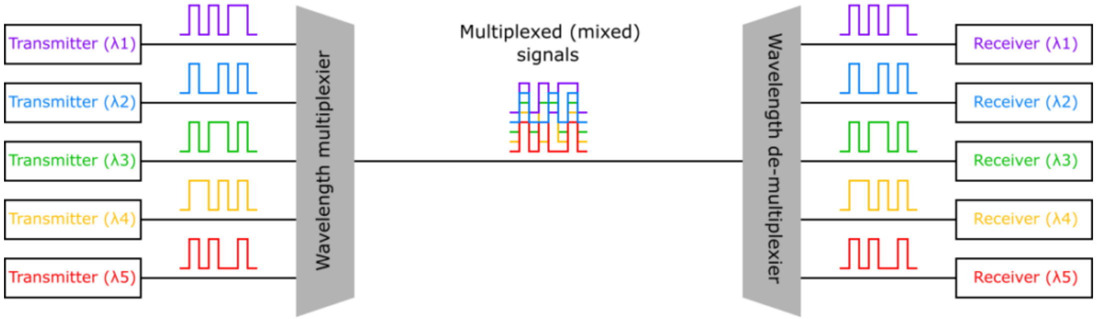
OPTICAL RECEIVER

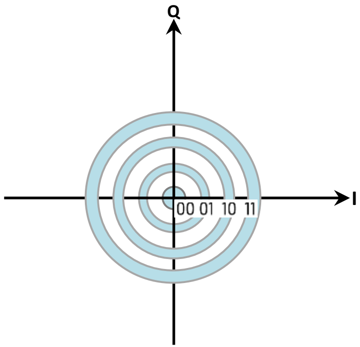


SPEED UP THE NETWORK

Wavelength

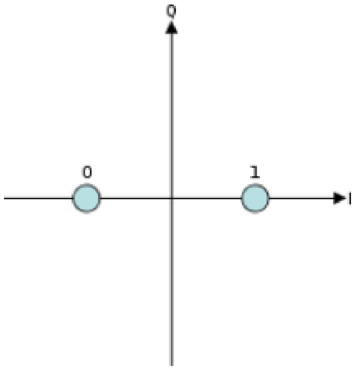


Amplitude/Intensity

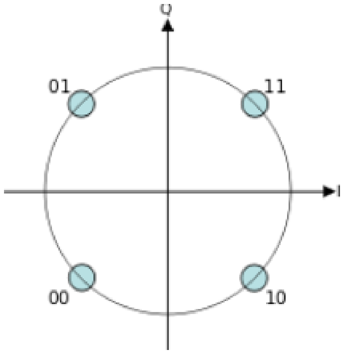


PAM4

Phase

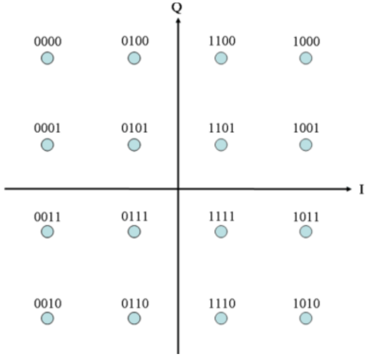


BPSK (Binary)



QPSK

Phase+amplitude

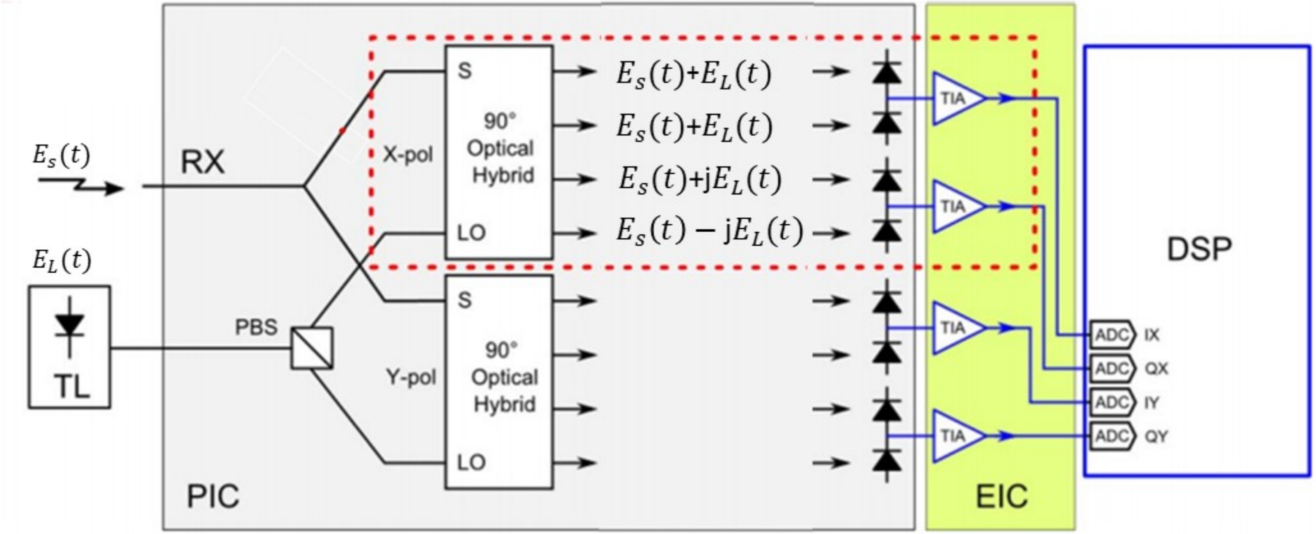


16-QAM

Phase
+
Amplitude
+
Polarization
…

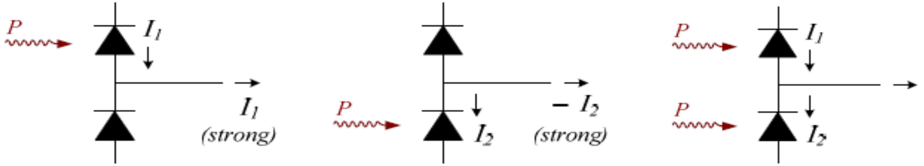
Coherent receivers

1. Local oscillator (LO) laser—as a phase reference
2. 90° optical hybrid
3. Balanced detectors / Electronic circuits
4. Digital Signal Processor



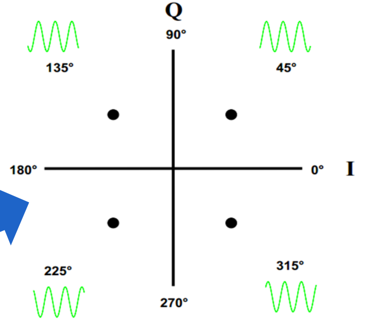
COHERENT RECEIVERS

Balanced detector



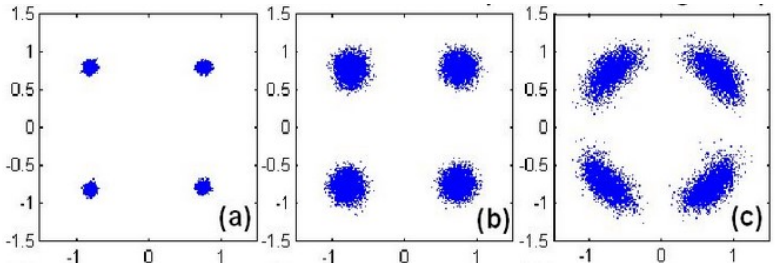
In phase $I_1(t) - I_4(t) = 4R\left|E_s(t)\right| \cdot \left|E_L(t)\right| \cdot \cos(2\pi\Delta f t + \phi(t))$

Quadrature $I_2(t) - I_3(t) = 4R\left|E_s(t)\right| \cdot \left|E_L(t)\right| \cdot \sin(2\pi\Delta f t + \phi(t))$



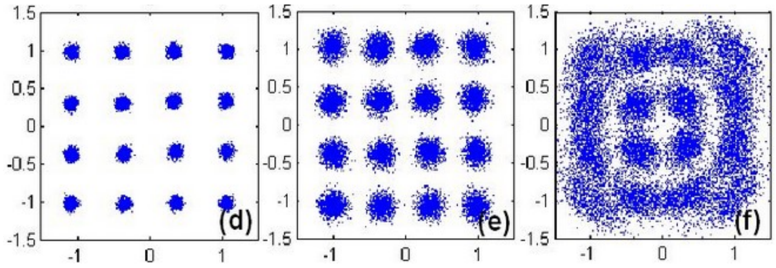
Local oscillator

Phase noise



QPSK

Phase noise



16QAM

LO: low phase noise→ narrow linewidth [spec for 400ZR : 500kHz]

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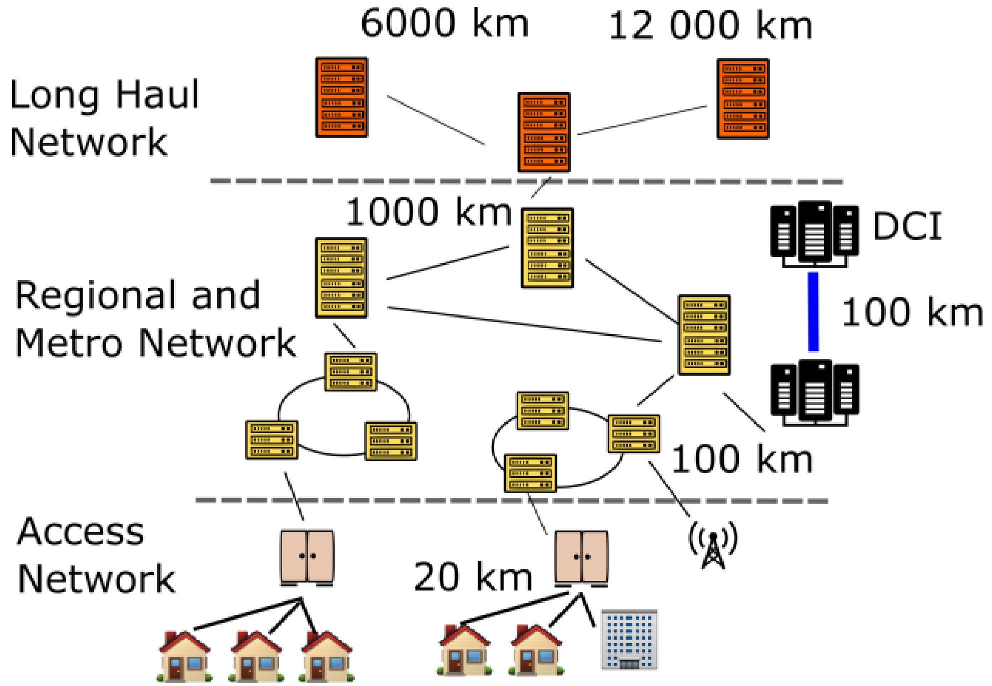
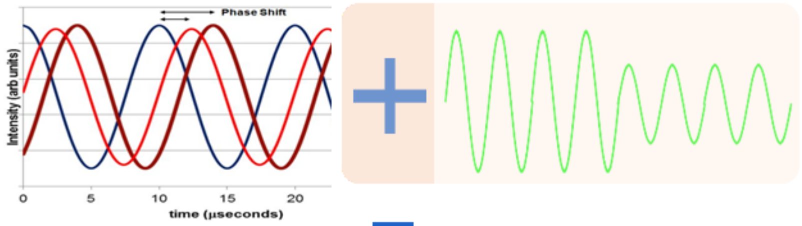
Which communication system should be used?



Antonin Gallet. Ph.D thesis 2019.

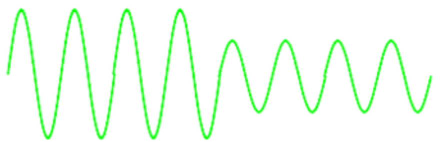
Coherent communication



Cost & power consumption

VS

Performance



Intensity modulation and direct detection(IMDD)

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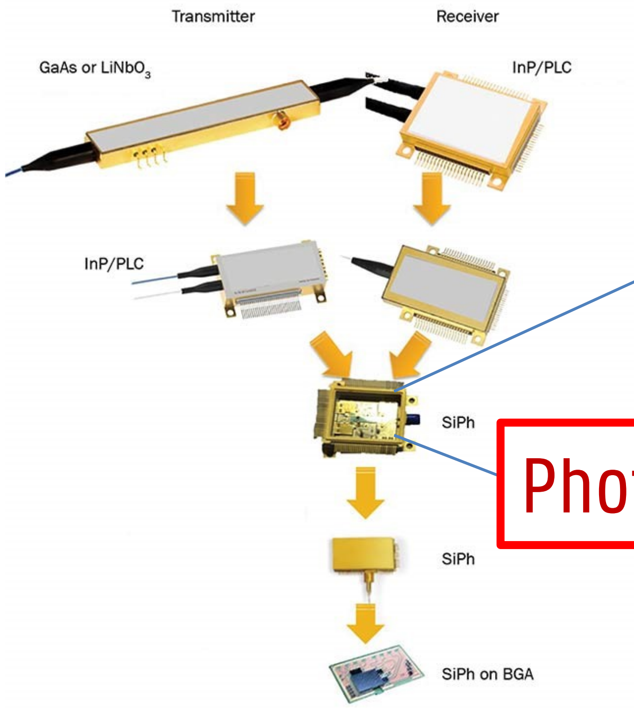
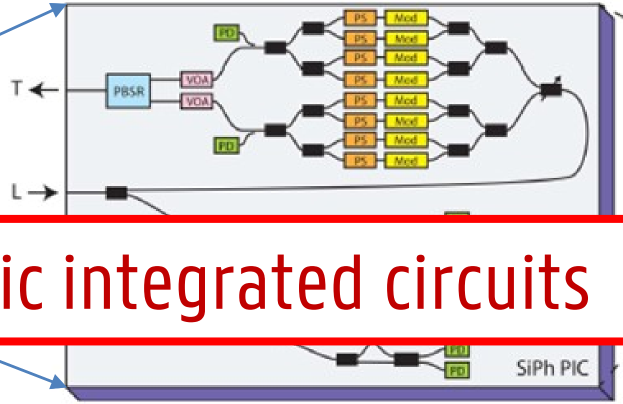
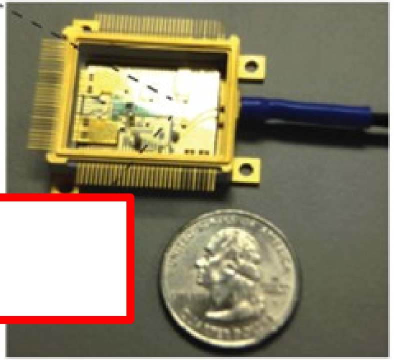
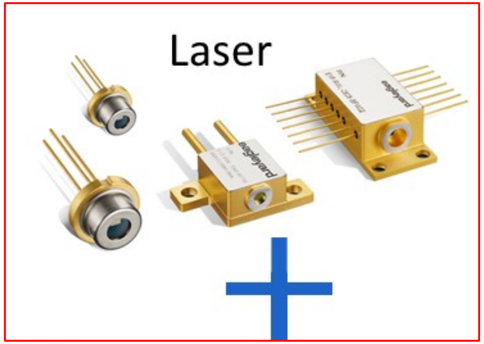
SMALLER, CHEAPER, FASTER!









Photonic integrated circuits

https://www.photonics.com/Articles/Trends_in_Silicon_Photonics_for_Fiber_Optic/p5/vo170/i1112/a64191

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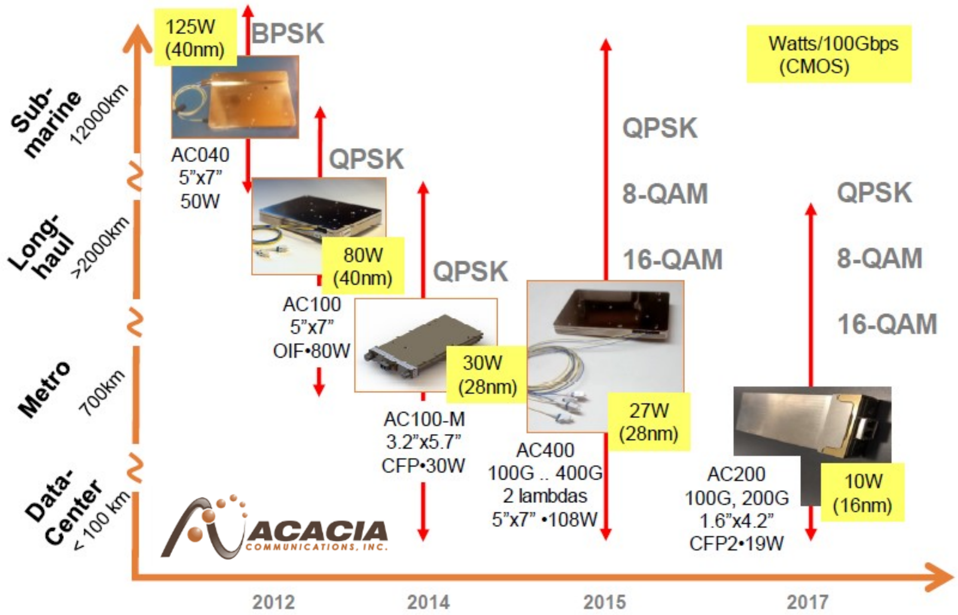
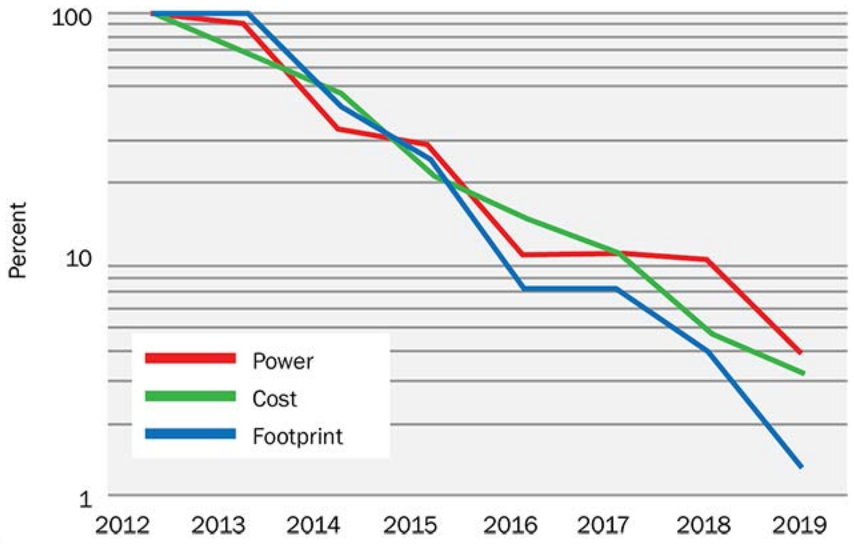
Smaller, cheaper, faster!



Evolution in power and density per 100Gps for coherent transceiver modules

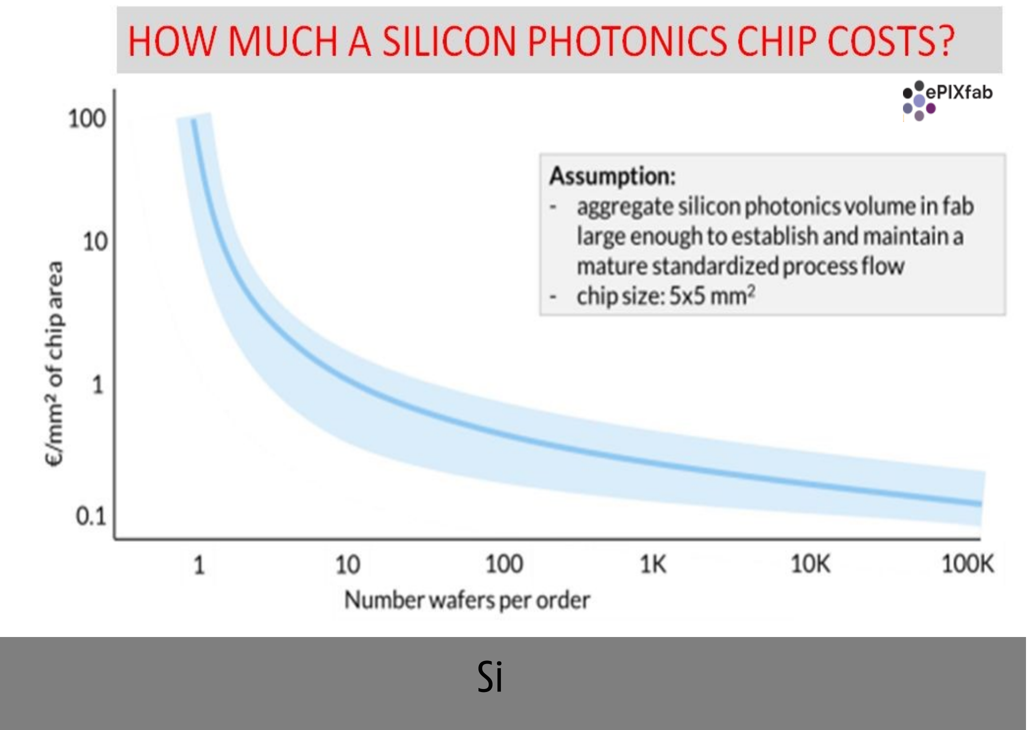
https://www.photonics.com/Articles/Trends_in_Silicon_Photonics_for_Fiber_Optic/p5/vo170/i1112/a64191

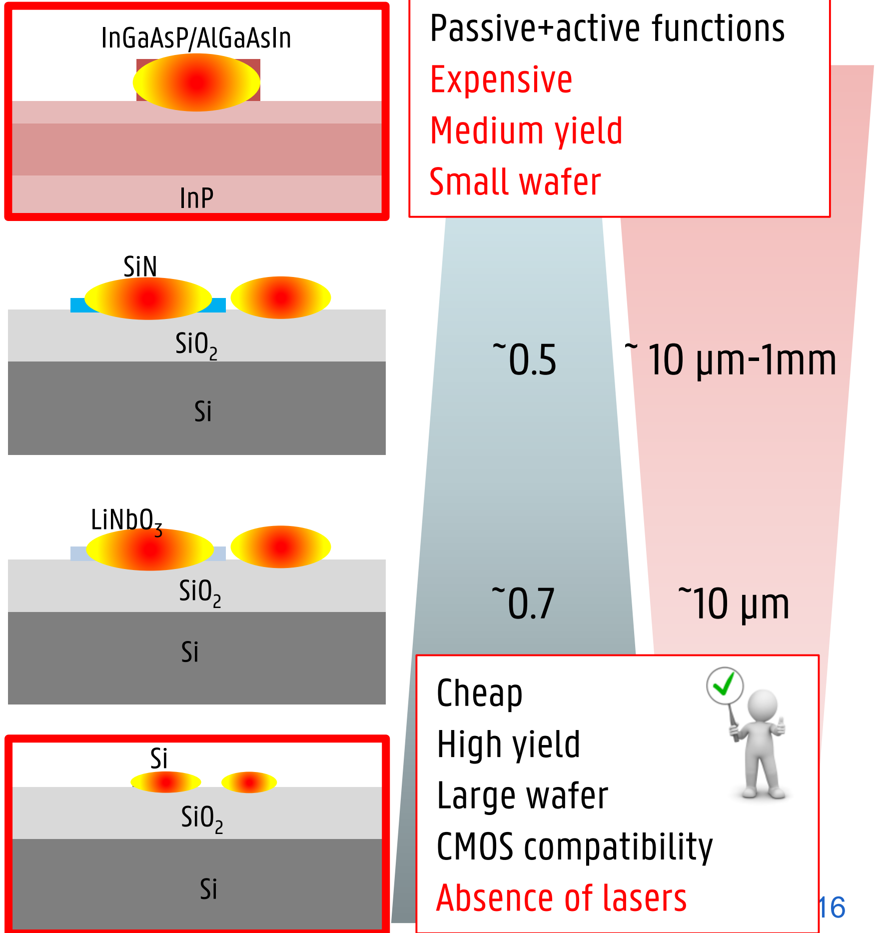


Power, cost, and footprint reduction in coherent communications per data transmission rate. Courtesy of Acacia Communications Inc

H. Zhang, and et. al., Opt. Express 26, 6943-6948 (2018)

PHOTONIC PLATFORMS



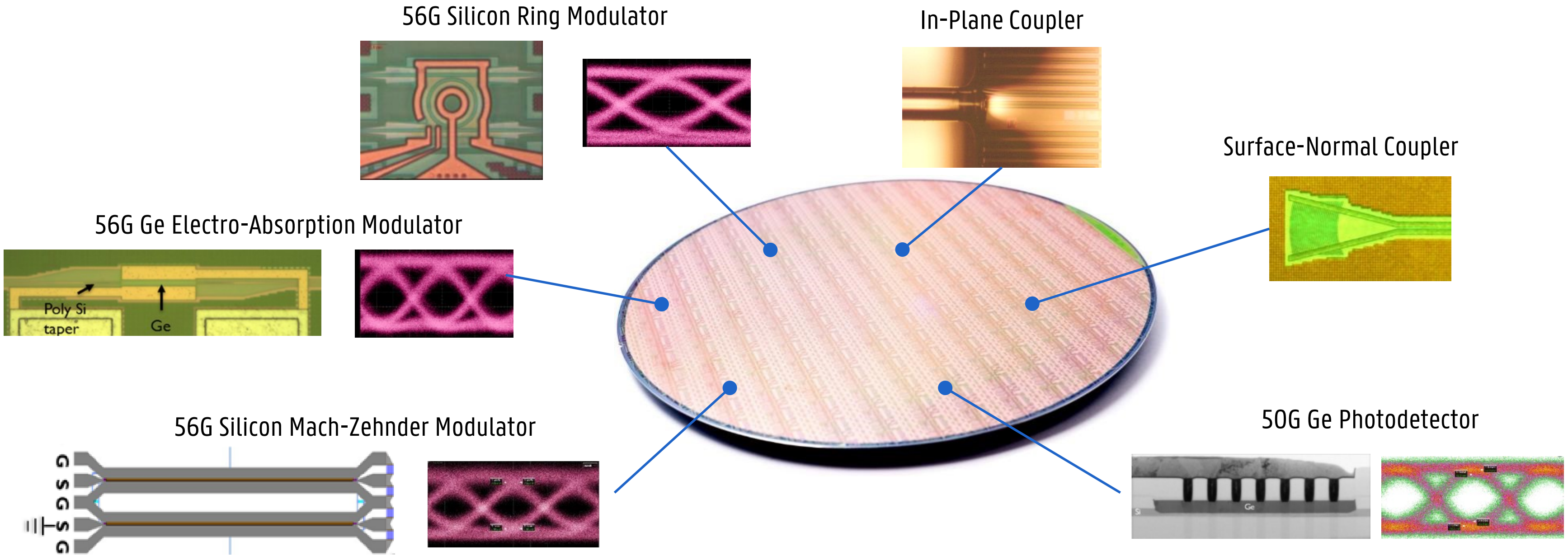


Passive+active functions
Expensive
Medium yield
Small wafer

Cheap
High yield
Large wafer
CMOS compatibility
Absence of lasers

Standing on the shoulders of giants

The imec iSiPP50G platform



Co-integration of the various building blocks in a single platform

Today available on 200 mm wafer size, moving to 300mm

95% compatible with CMOS130 in commercial foundries

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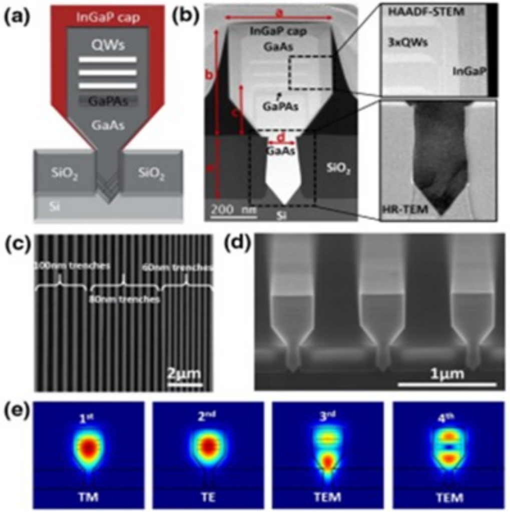
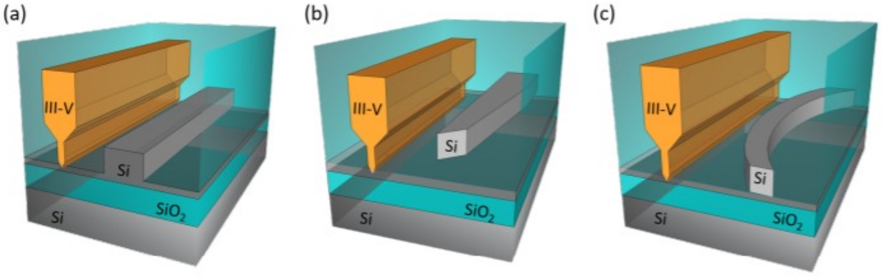
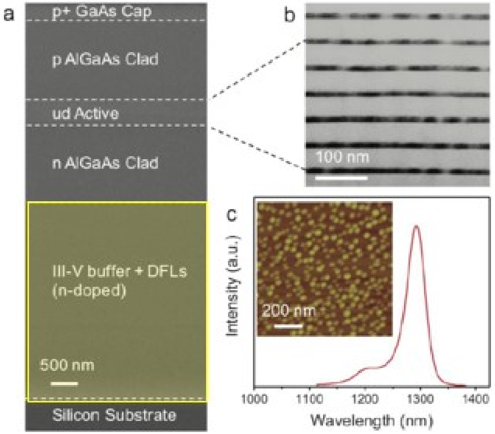
ULTIMATE SOLUTION—EPITAXIAL GROWTH OF III-V ON SI

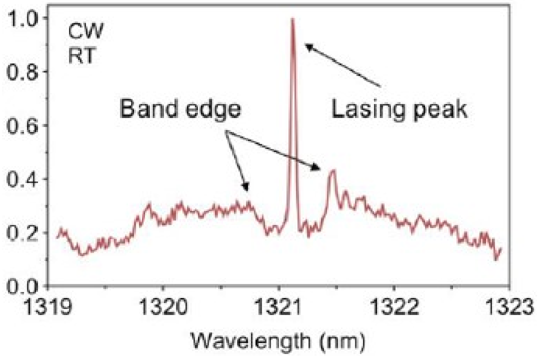


Y. Shi, and et.al, Optica 4(12), p.1468, (2017)



Y. Shi, and et.al, 27,37781 Optics Express (2019)



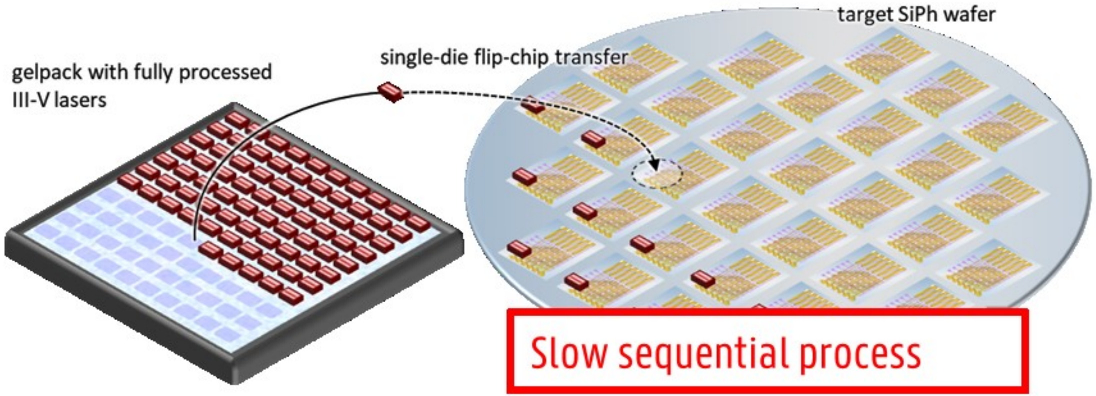


Yi Wang, and et.al, Optica 5, 528-533 (2018)

Still a lot of basic work to be done

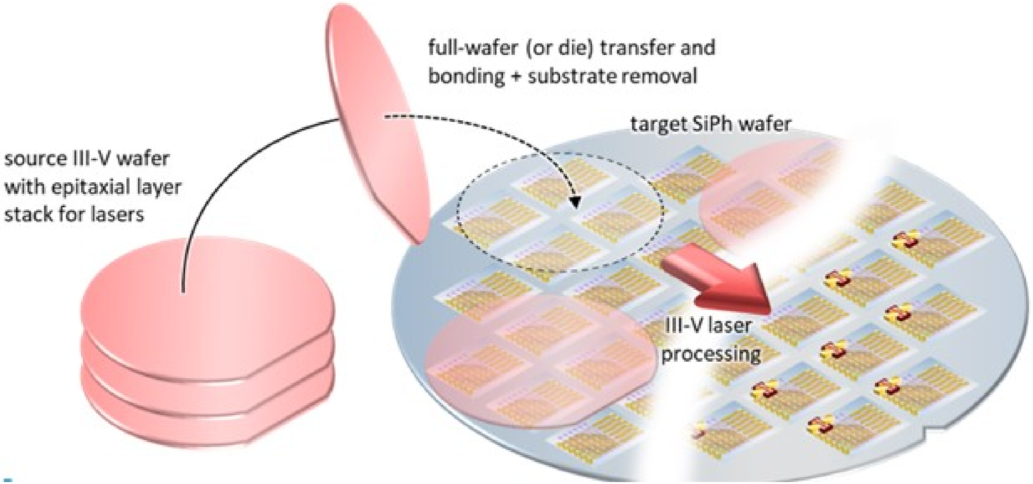
Established III-V-on-silico

Flip-chip/pick-and-place integration



Slow sequential process

III-V/silicon wafer bonding



ntel Silicon Photonics 100G PSM4 QFSP28 Transceiver

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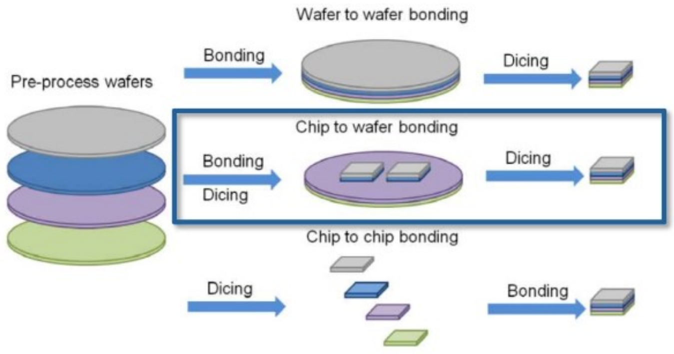
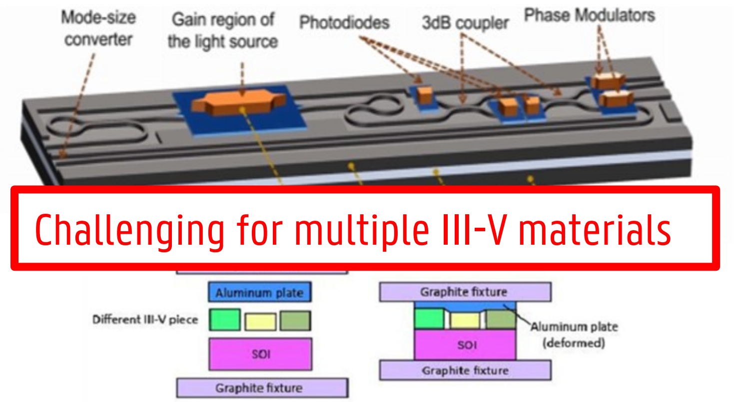
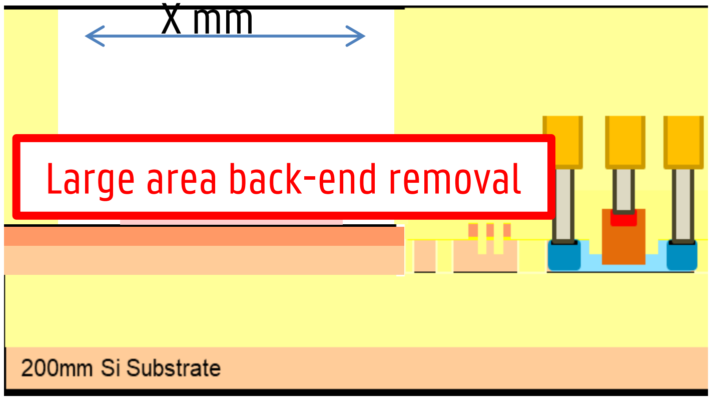
CHALLENGES FACED BY WAFER BONDING

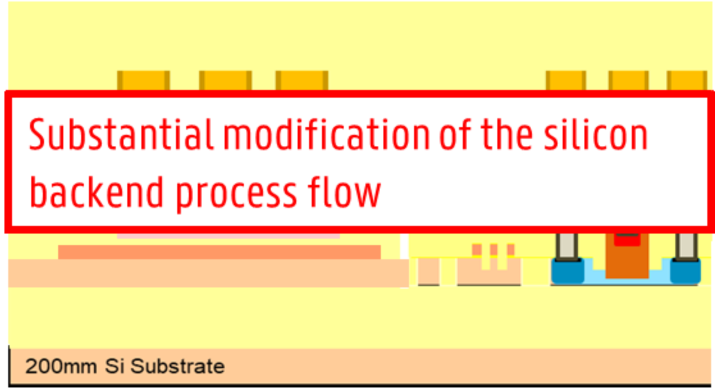


Source: Nanyang Technological University, Singapore



T. Komljenovic,et. al, Proceedings of the IEEE, vol. 106, no. 12, pp. 2246-2257, 2018





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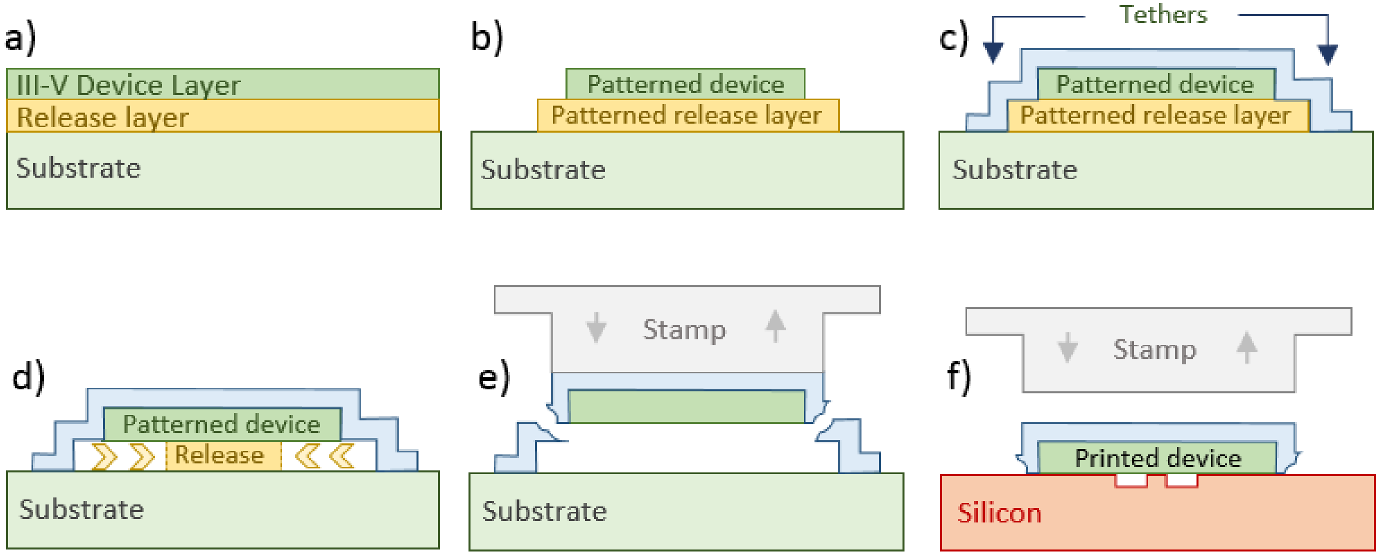
Micro-transfer printing



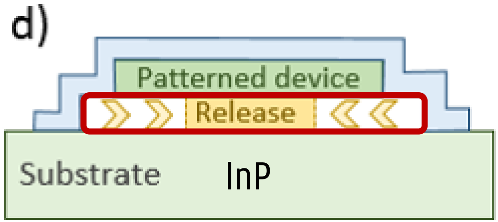
Transfer of <u>released, micro-scale</u> III-V devices to a Si target wafer

Micro-transfer printing—choice of the release layer

Candidate:

InAlAs

InGaAs

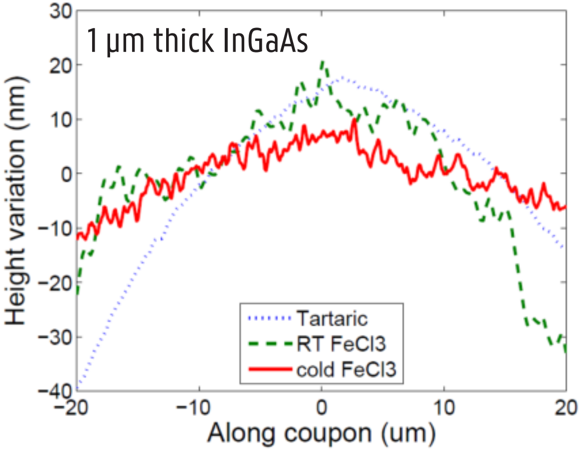


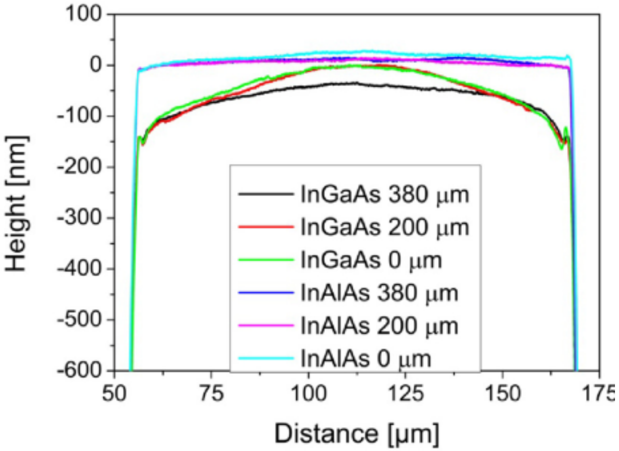
Selectivity to InP:

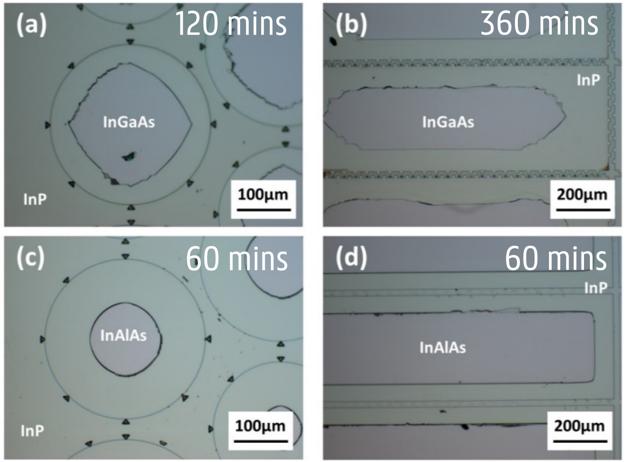
InAlAs: > 4,000

InGaAs:> 1,000

Etchant: cold $FeCl_3$:H_2O

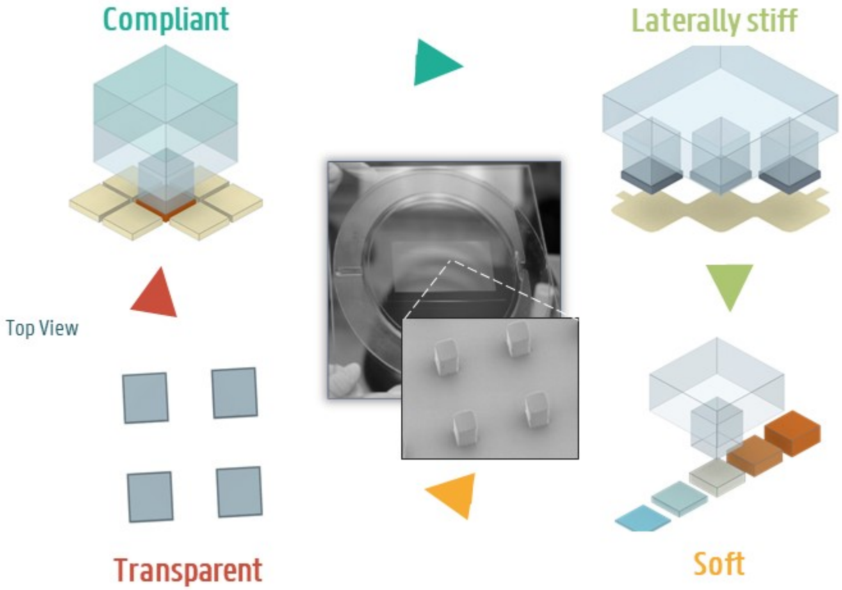


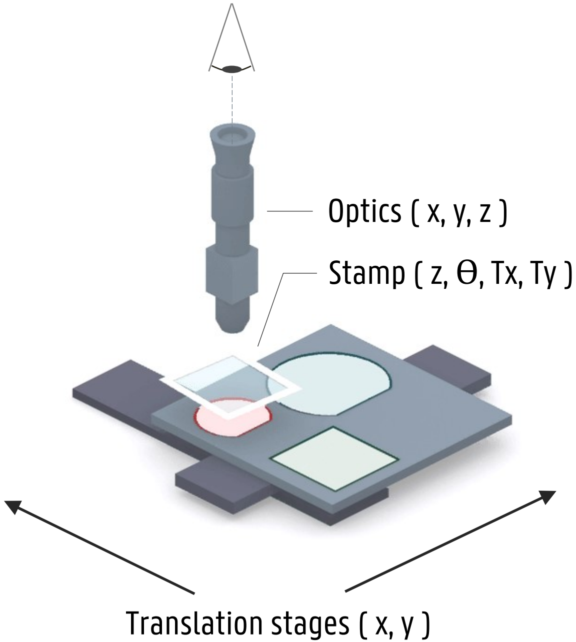




J. O'Callaghan, 7(12) p.4408-4414, Optical Materials Express,2017.

MICRO-TRANSFER PRINTING—STAMP AND TRANSFER PRINTING SYSTEM

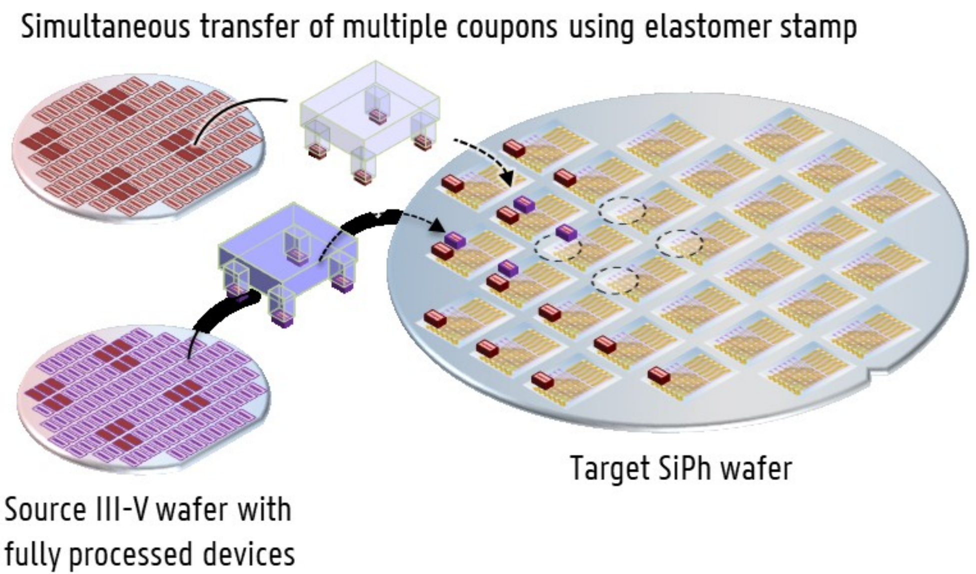


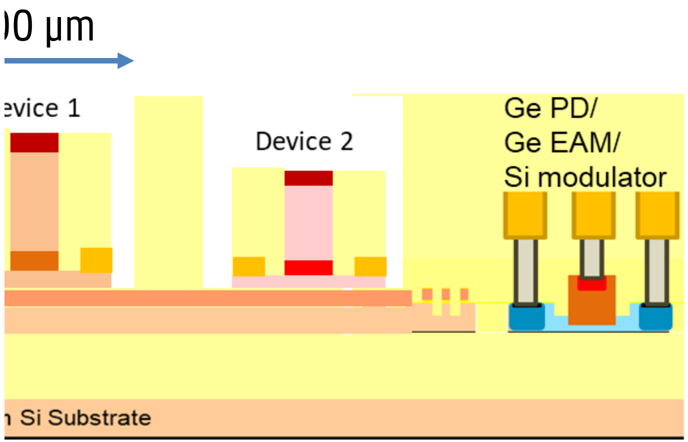


Position tolerance of ±1.5 µm at 3σ in large arrays

±0.5 µm when printed in small arrays

MICRO-TRANSFER PRINTING—INTEGRATION OF III-V/SI PICS





µTP combines advantages of flip-chip/pick-and-place and die-to-wafer bonding.

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Micro-transfer printing—save expensive materials

Transfer printing:

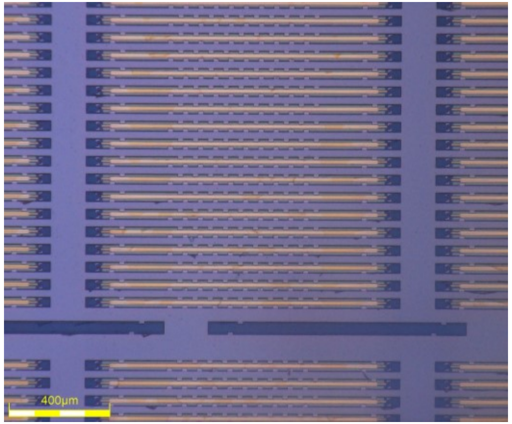
Coupon width: e.g. 50 µm

Coupon length: e.g. 1.5 mm (device length ~1.4um)

Pitch_y: 70 µm

Pitch_x: ~1.6 mm

Potential of recycle and resut the thick substrate

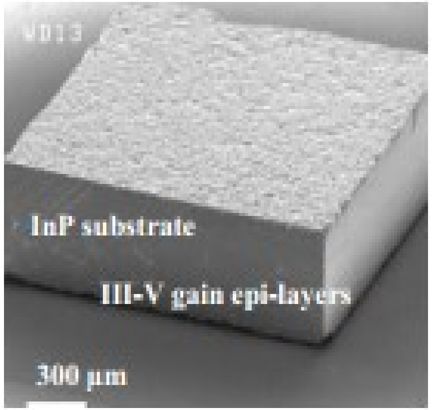


Pick-and-place:

Min III-V die size: 600 µm X 300 µm (0201)

For a component with size of 1.4 mm X 50 µm

A 1.5 mm X 300 µm III-V die is required



https://www.manncorp.com/how-manufacturers-specify-equipment

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WHAT DID I DO IN MY PHD YEARS?

1. Transfer-printed Fiber-To-The-Home (FTTH) transceivers
    1. Transfer printing O-band photodiodes
    2. Transfer-printed DFB lasers
    3. **Four-channel point-to-point FTTH transceiver array**
    4. **A single-channel point-to-point FTTH transceiver based on the co-integration of DFB laser and O-band PD**
2. Integration of III-V-on-Si coherent receivers through micro-transfer printing
    1. **Transfer-printed widely tunable and narrow linewidth laser**
    2. Transfer-printed coherent receiver on a passive PIC
    3. **Integrated coherent receiver based on the imec iSiPP25/50G platform**

What did I do in my PhD years?

1. Transfer-printed Fiber-To-The-Home (FTTH) transceivers
    1. Transfer printing O-band photodiodes
    2. Transfer-printed DFB lasers
    3. **Four-channel point-to-point FTTH transceiver array**
    4. **A single-channel point-to-point FTTH transceiver based on the co-integration of DFB laser and O-band PD**
2. Integration of III-V-on-Si coherent receivers through micro-transfer printing
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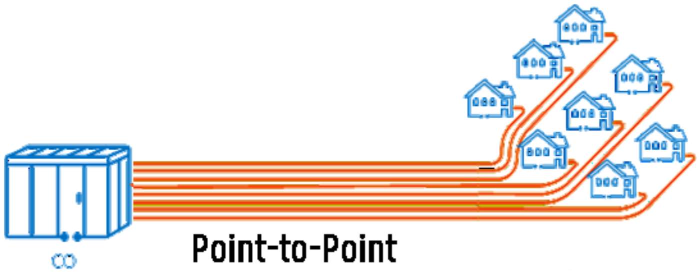
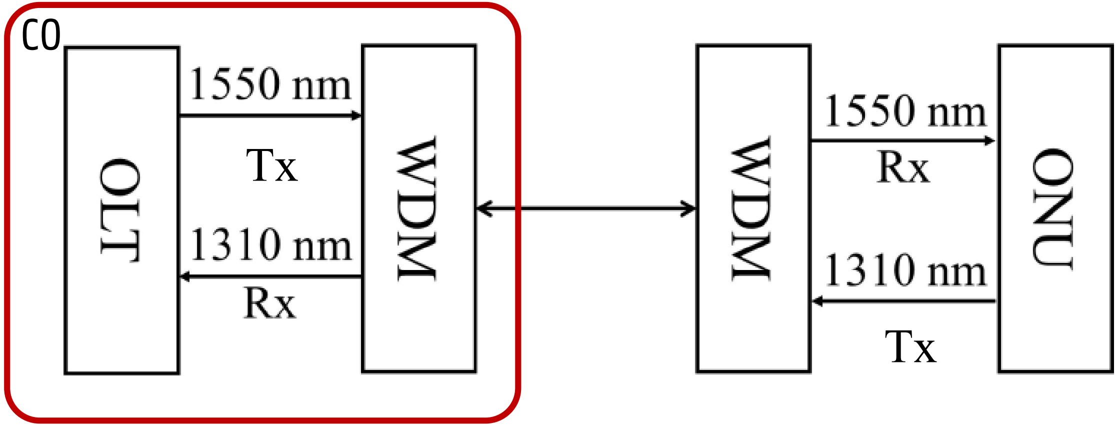
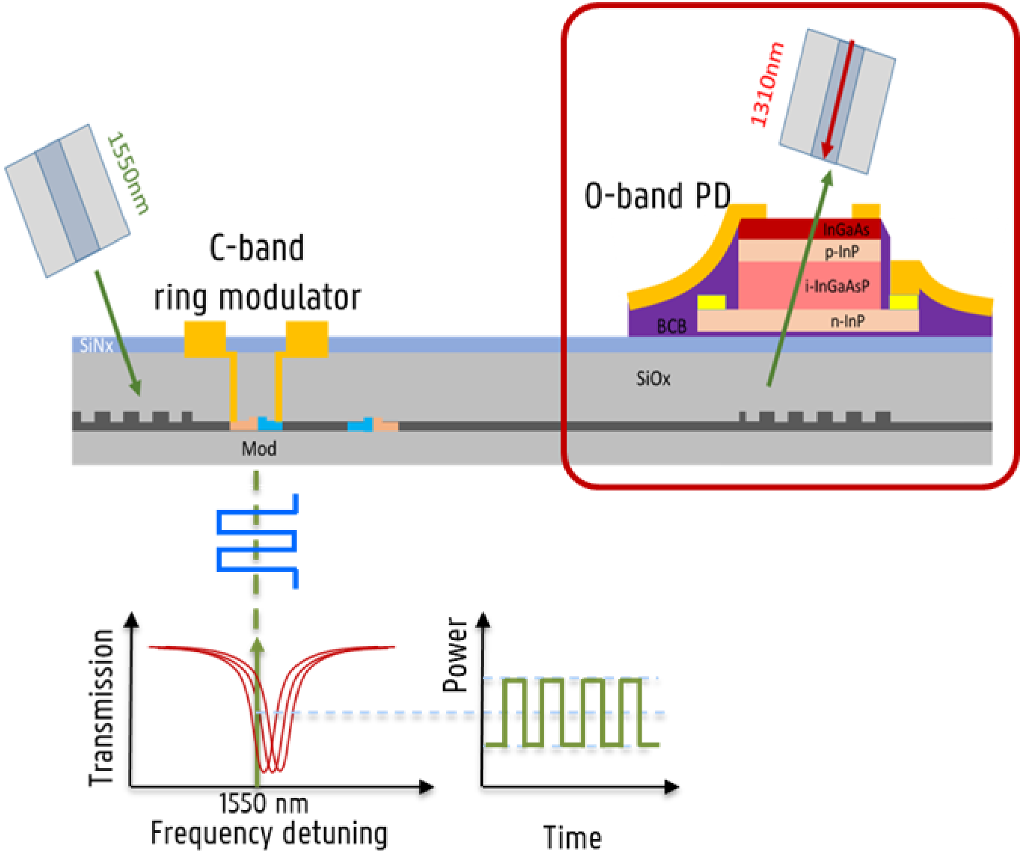
Fiber-To-The-Home

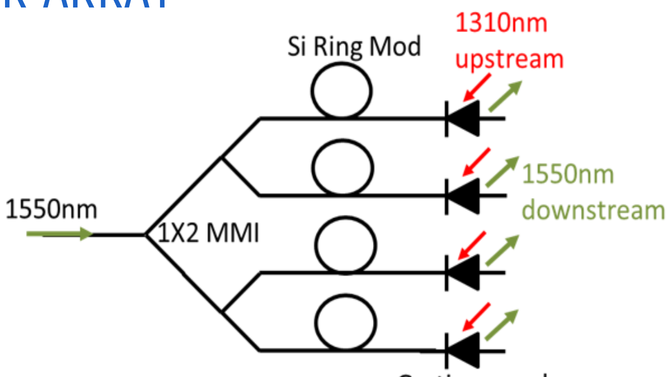


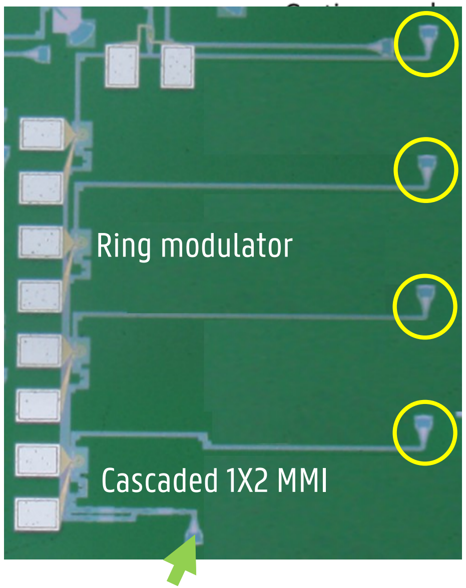
Higher bandwidth
Good service isolation
Good security
Long reach
Dedicated fiber line for each end user
Large number of transceivers in the CO



Four-channel Point-to-Point FTTH transceiver array







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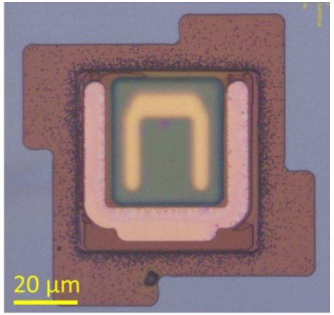
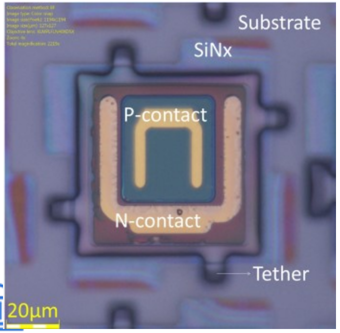
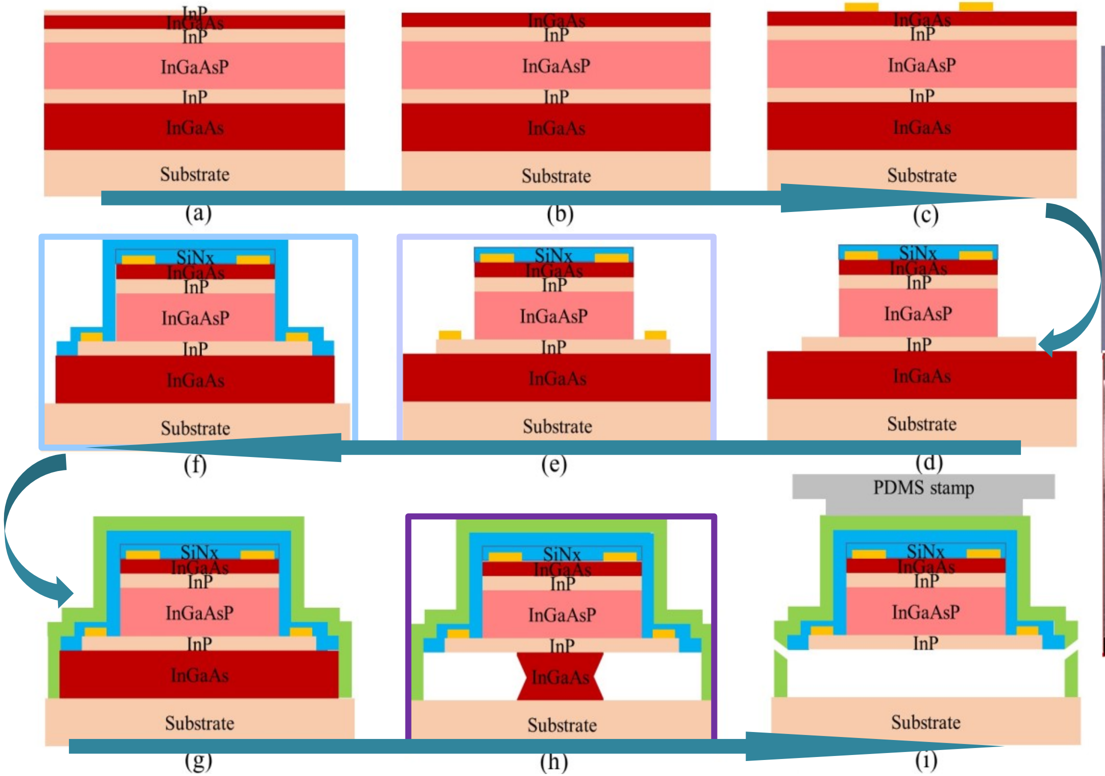
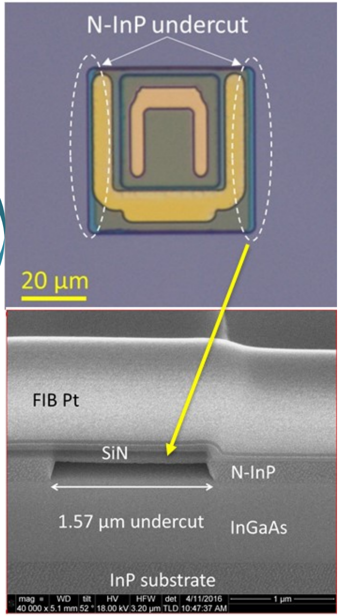
Pre-fabrication of O-band PDs on the source wafer



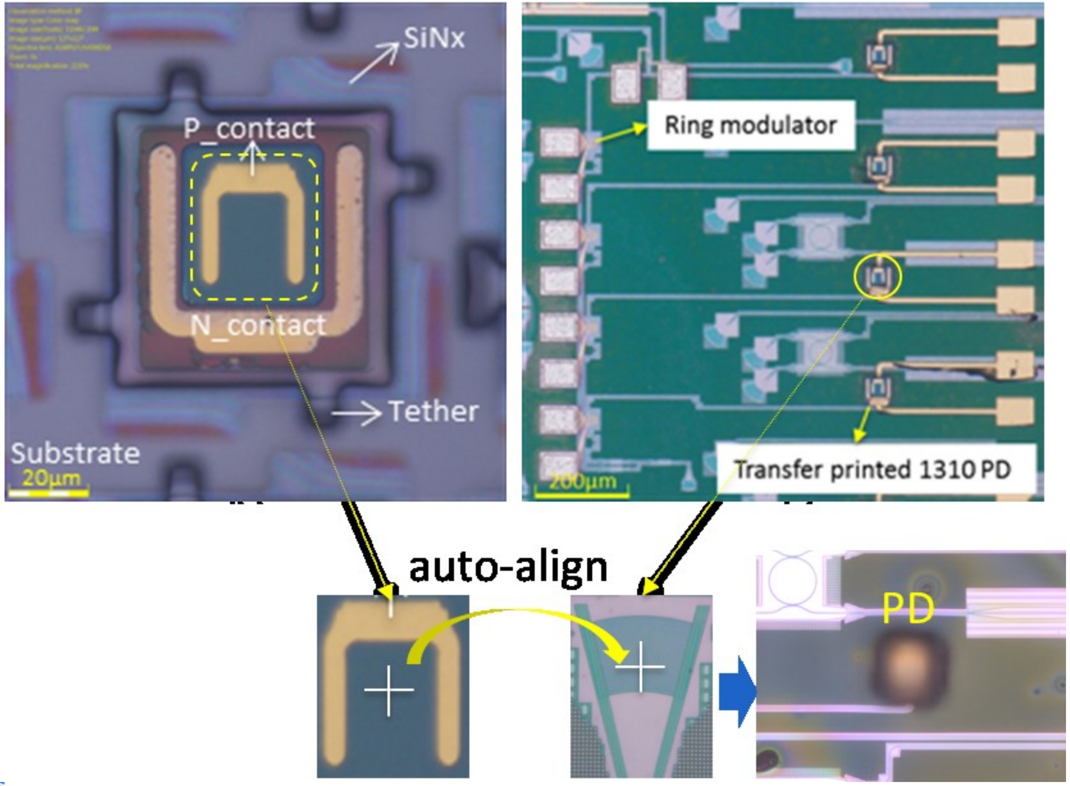
1 µm InGaAs release layer
Release: 100 mins
Etchant:$FeCl_3$:H_2O @5ºC



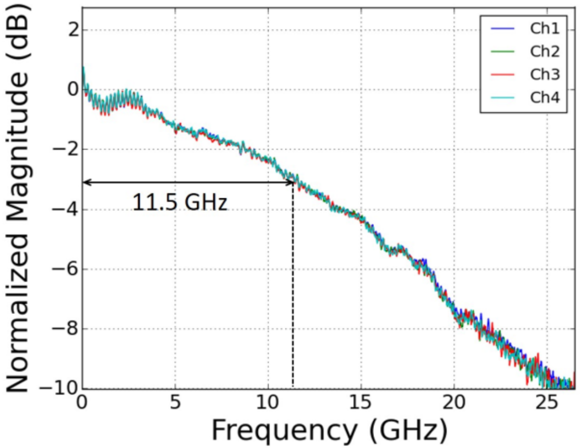




Transfer print pre-fabricated O-band PDs on an iSiPP25G chip



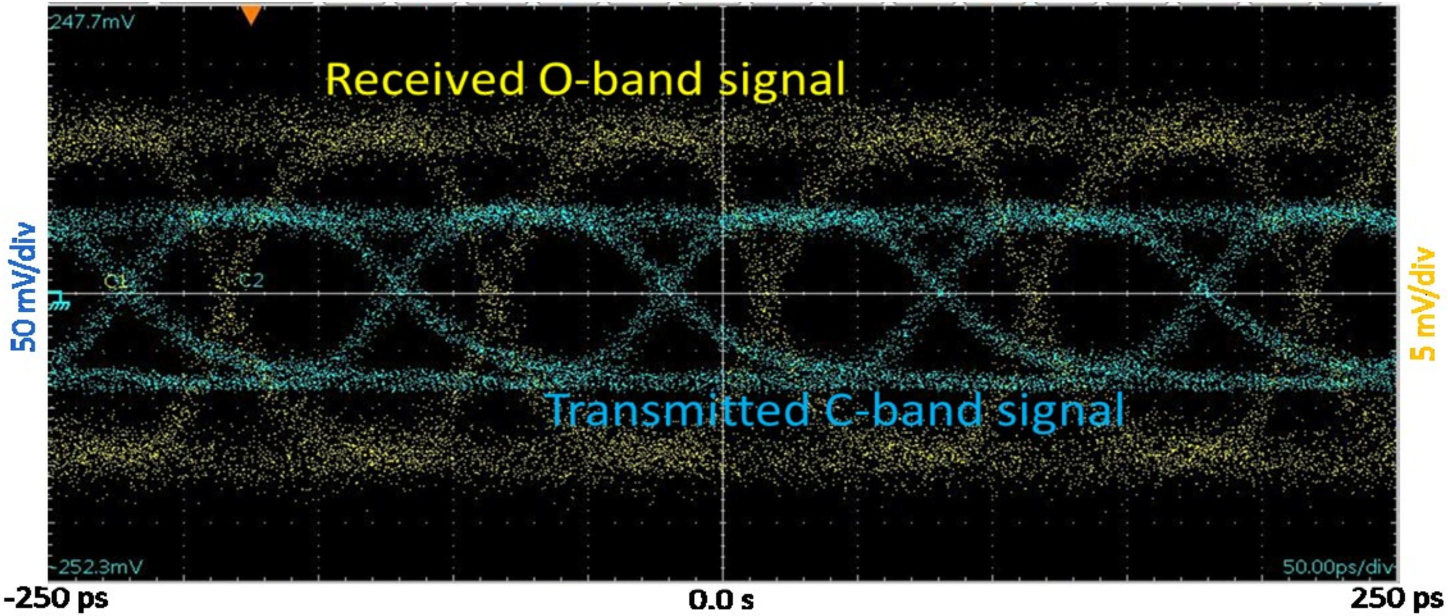
Responsivity in O-band : ~0.4 A/W
Responsivity in C-band : 0.025-0.03 mA/W



Demonstration of the transceiver array

Signal format : NRZ-PRBS

Error-free operation demonstrated



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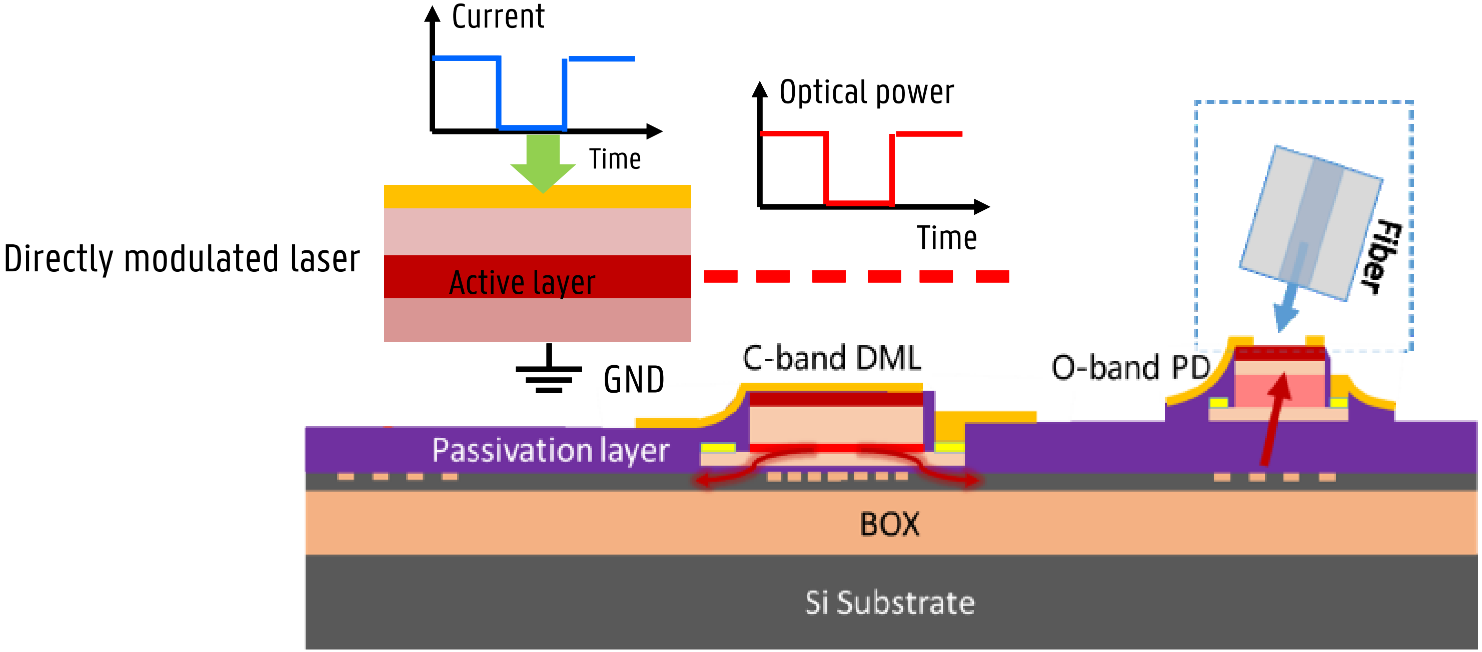
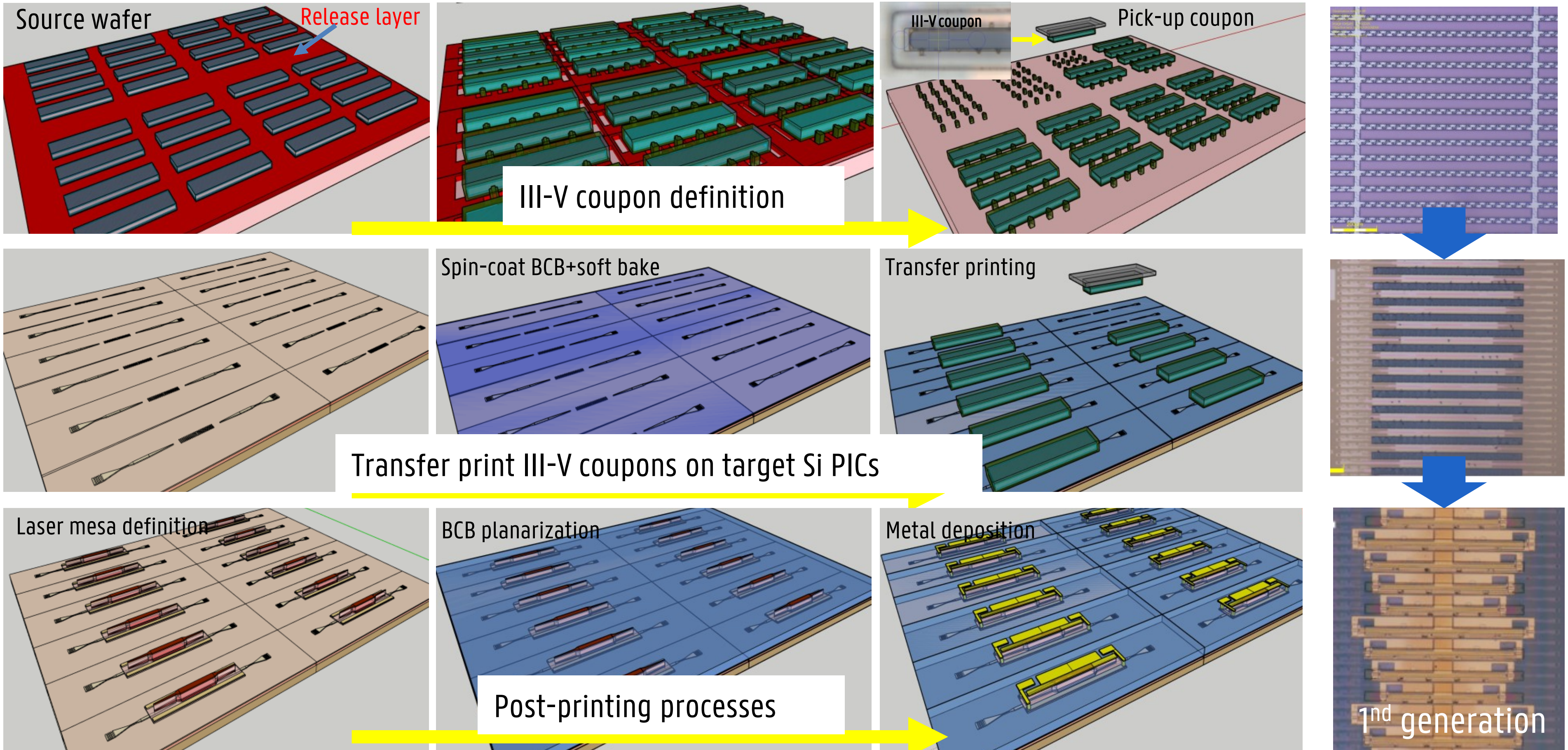
SINGLE CHANNEL FTTH TRANSCEIVER

Co-integration of a DFB laser (transmitter) and an O-band PD(receiver) on a passive PIC

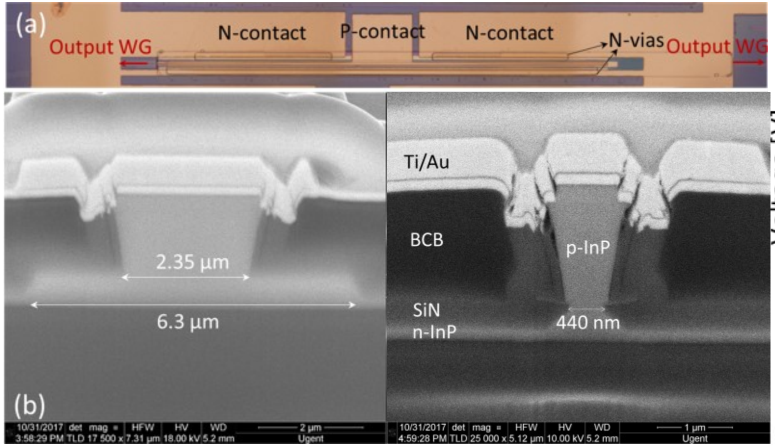
Si waveguide circuit: 400 nm thick, 180 nm single-step etch.

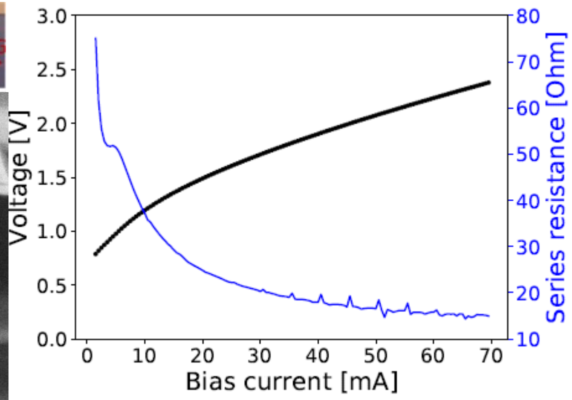


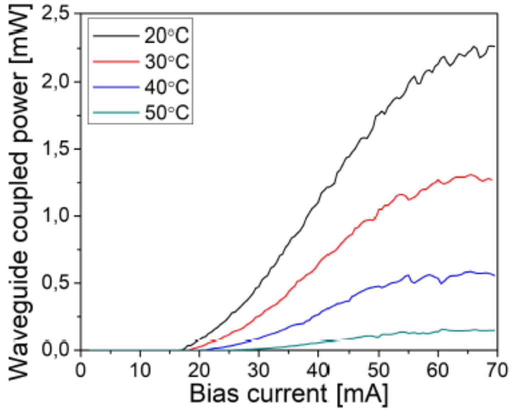
Micro-transfer-printed III-V-on-Si DFB lasers



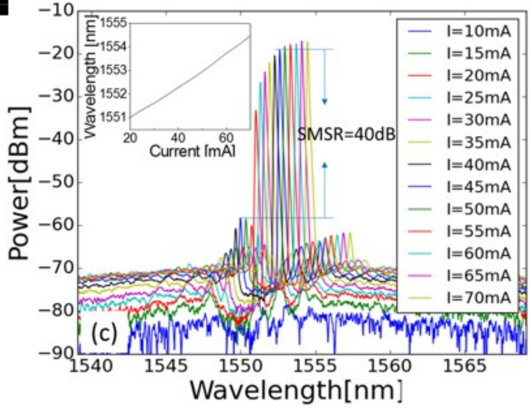
Micro-transfer-printed III-V-on-Si DFB lasers—2nd generation

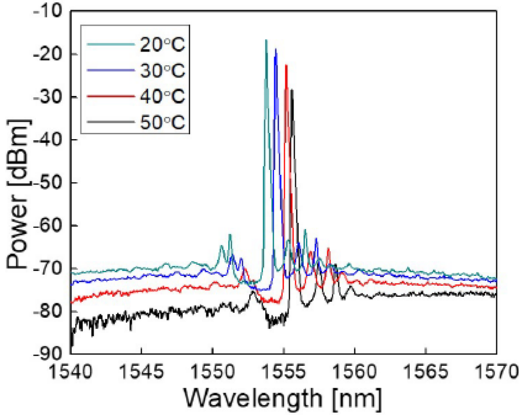






- Grating period: 477 nm(2nd order)
- Grating length: 300 µm
- Lateral misalignment: 240 nm
- KL= 5.16
- SMSR: >40 dB
- Threshold: 18 mA
- Waveguide coupled power: 2 mW





SINGLE CHANNEL FTTH TRANSCEIVER

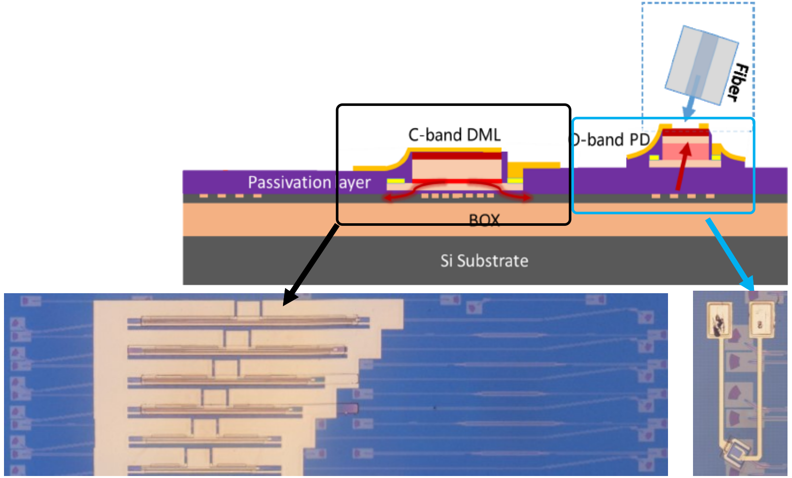
Signal format : NRZ-PRBS

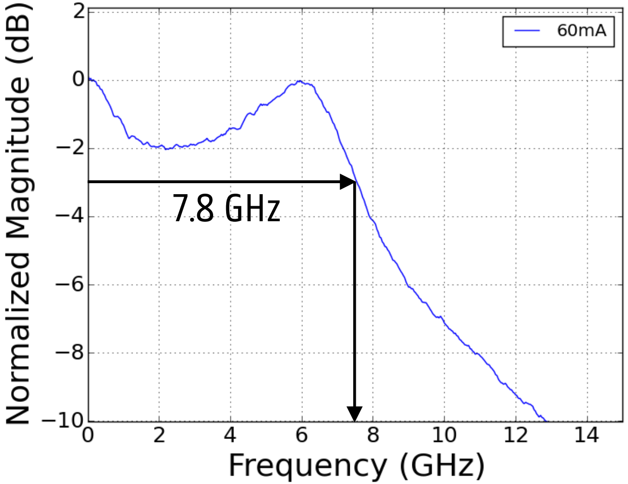
DFB laser small signal 3-dB bandwidth: ~7.8 GHz

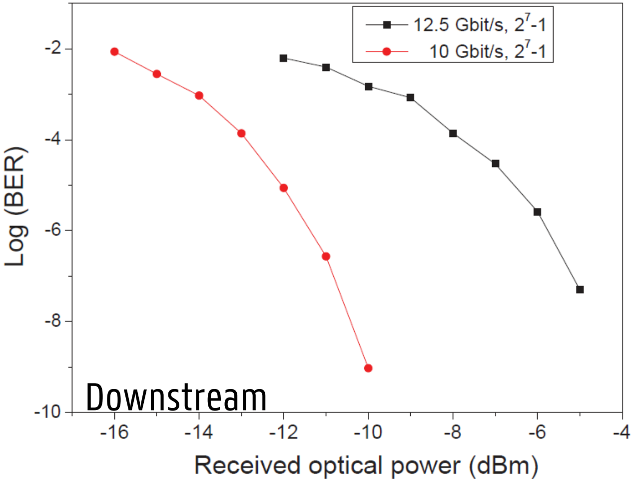
DFB fiber coupled power: 0.45 mW

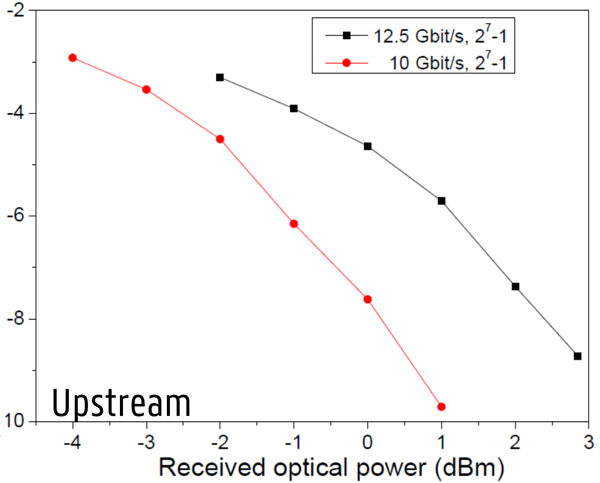
Responsivity of the PD in O-band: ~0.3 A/W

Error-free operation @ 10 Gbit/s









What did I do in my Ph.D years?

1. Transfer-printed Fiber-To-The-Home (FTTH) transceivers
    1. Transfer printing O-band photodiodes
    2. Transfer-printed DFB lasers
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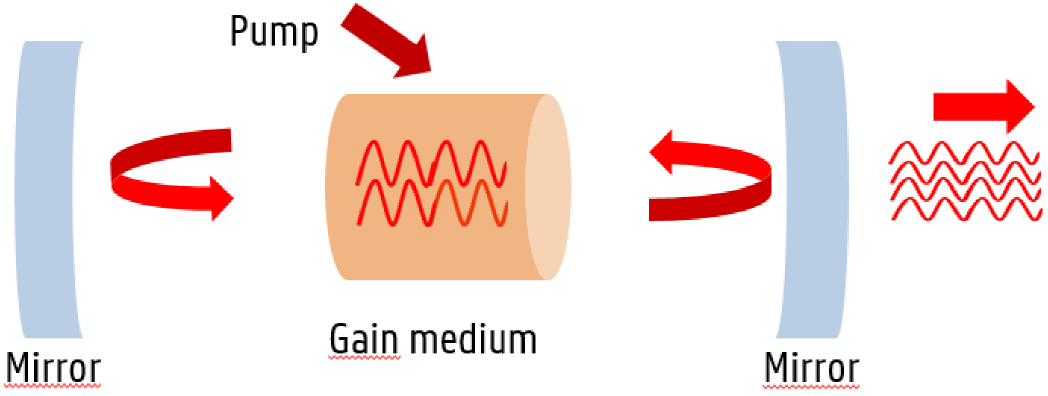
Laser spectral linewidth



$$\Delta\nu_{laser} = \frac{v_g^2 \hbar\nu g_{th} n_{sp} \alpha_m}{8\pi P}(1+\alpha^2)$$

$$\alpha_m = -L^{-1} ln(r_m)$$

1. Low cavity loss(g_{th}, r_m)
2. Long cavity (L)
3. High output power (P)
4. Low linewidth broadening factor (α)
5. Stable pump

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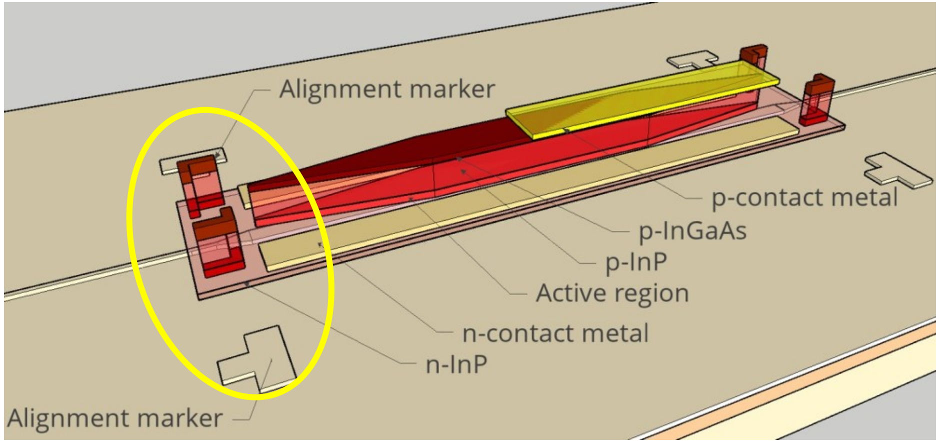
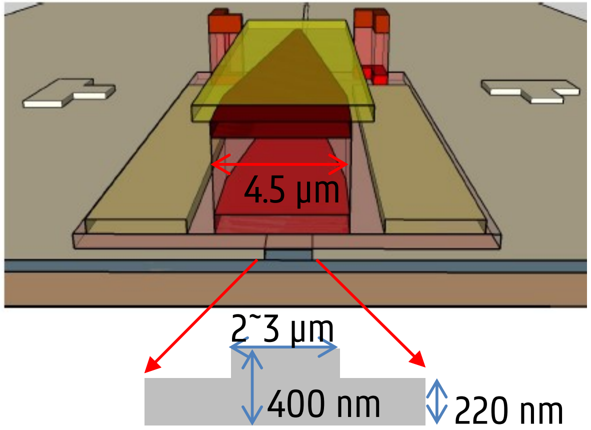
Alignment tolerant III-V/Si taper structure

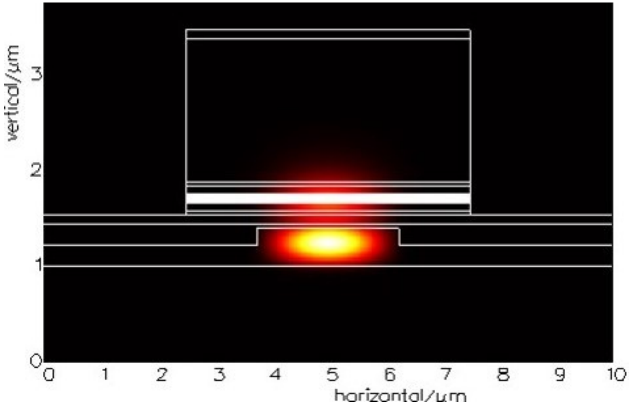
Position tolerance of ±1.5 µm at 3σ in large arrays

±0.5 µm when printed in small arrays

1. Reduce the optical confinement factor in III-V
2. Use a wide III-V waveguide

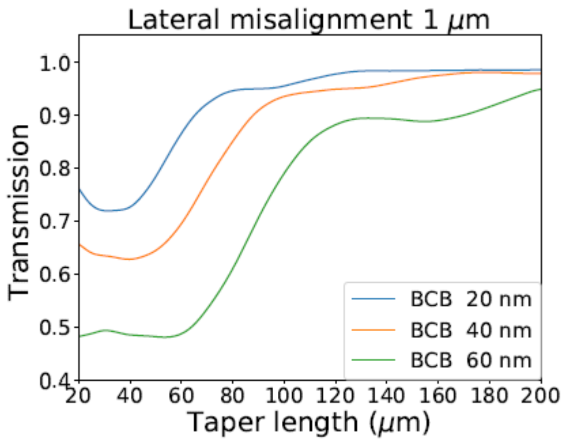


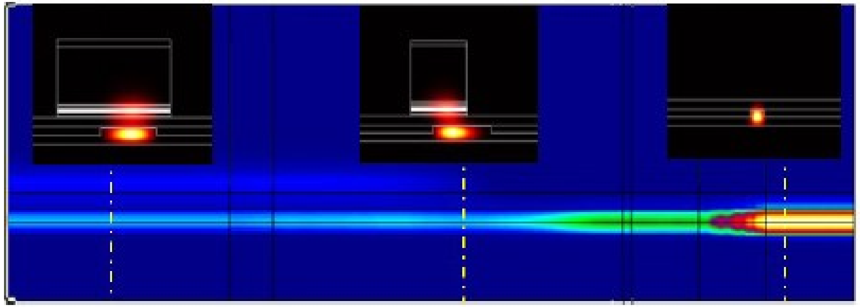




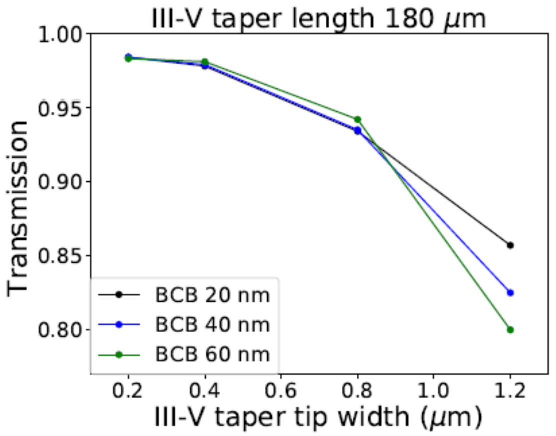
Alignment tolerant III-V/Si taper structure

III-V waveguide width> 4.5 µm
Si waveguide width : 2 ~3 µm
BCB thickness < 60 nm
III-V taper tip width <600 nm
III-V taper length >180 µm





BCB: 20 nm
III-V taper length : 180 µm



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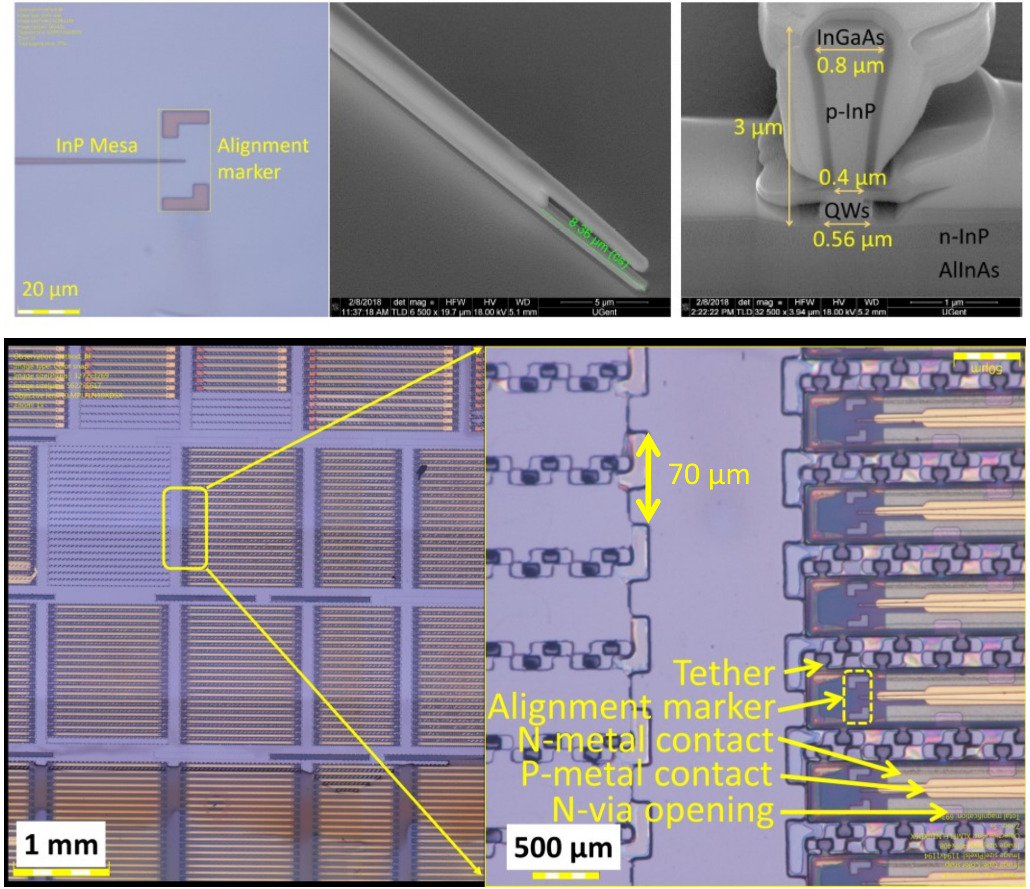
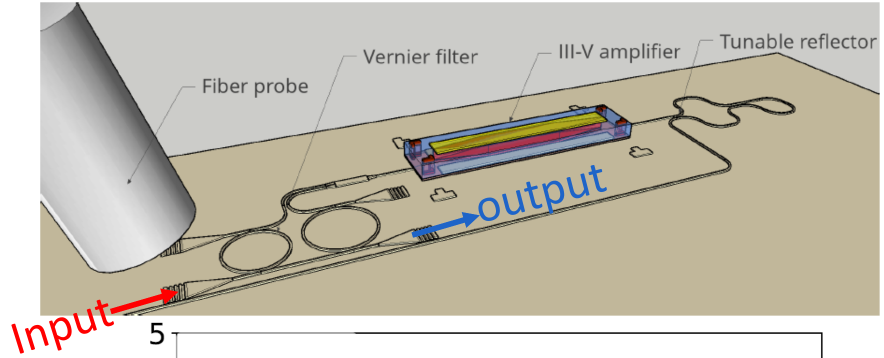
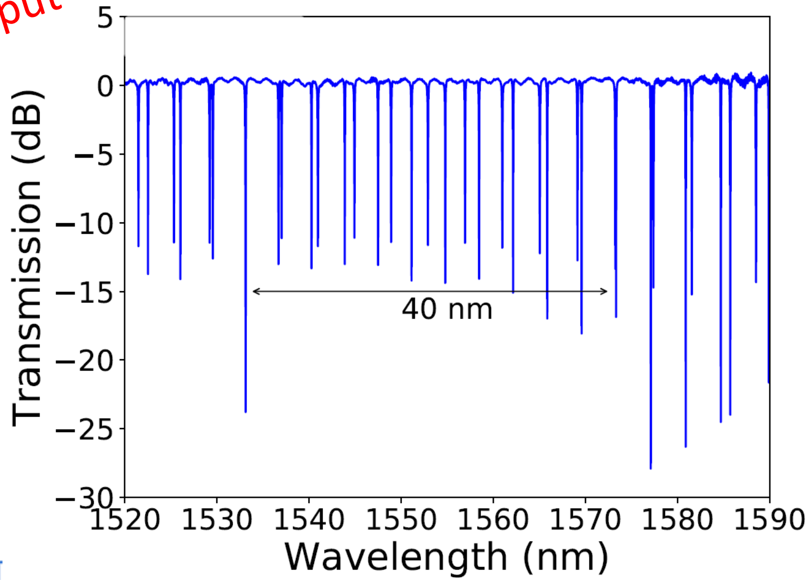
Pre-fabrication of SOAs on the InP substrate

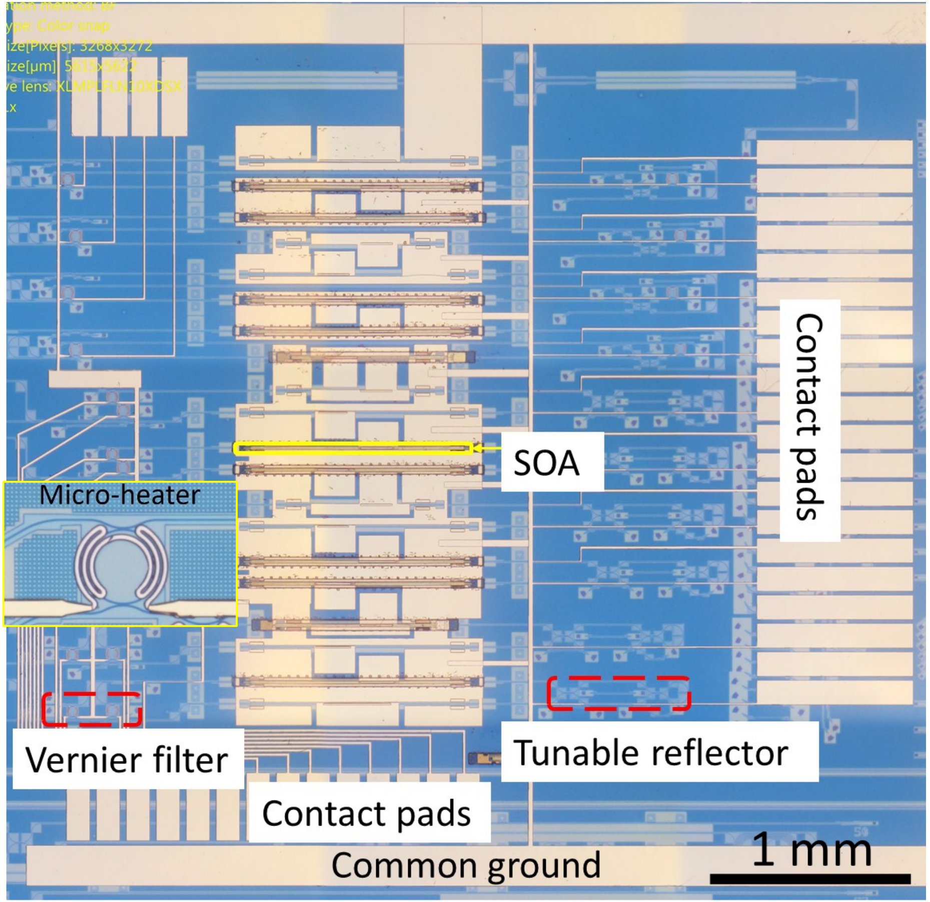
Release layer: 500 nm InAlAs
III-V mesa width: 4.5 µm
Taper length： 200 µm
Coupon pitch: 70 µm
SOA length : 1.16 mm/1.36mm



Transfer-printed III-V-on-Si widely tunable lasers







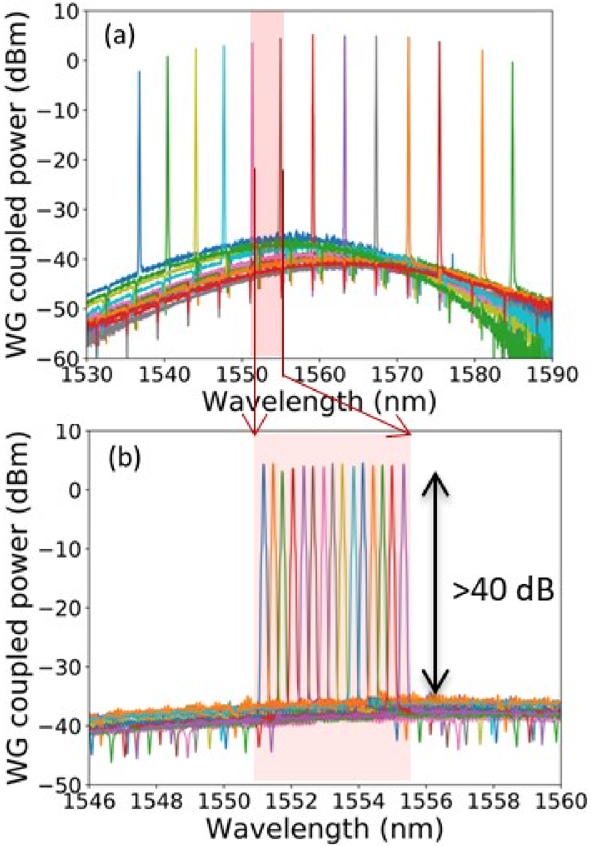
Transfer-printed III-V-on-Si widely tunable lasers

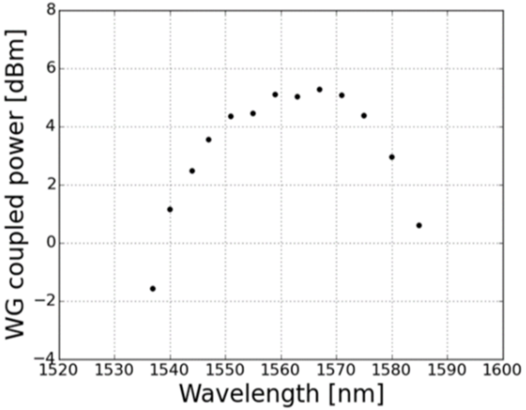
Tuning range: 50 nm

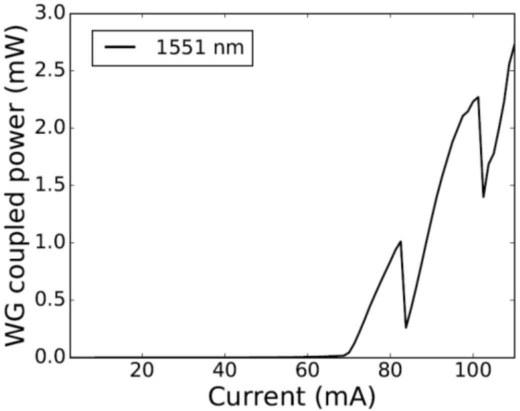
SMSR: >40 dB

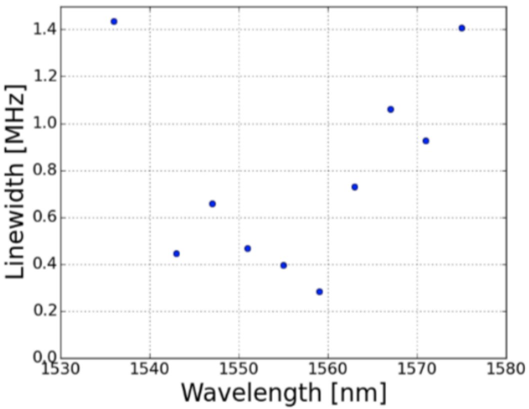
Peak output power: >5 dBm

Minimum Linewidth: 300 KHz







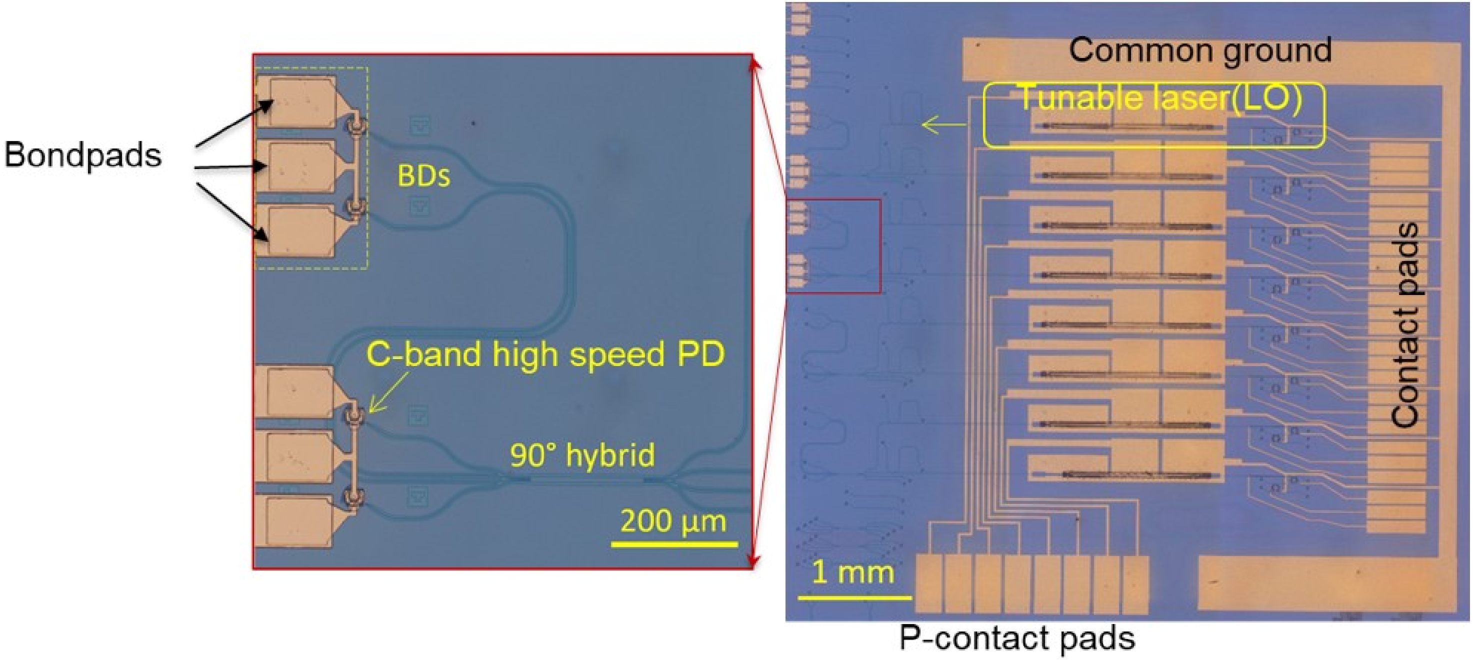


III-V-on-Si integrated coherent receiver (ICR) on passive PICs

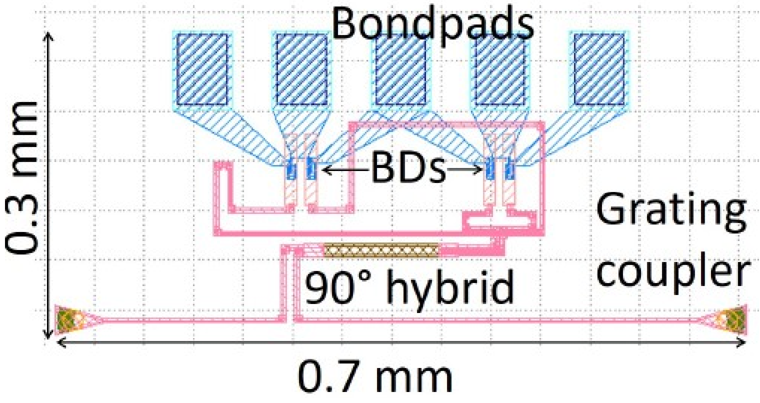
Si PICs:

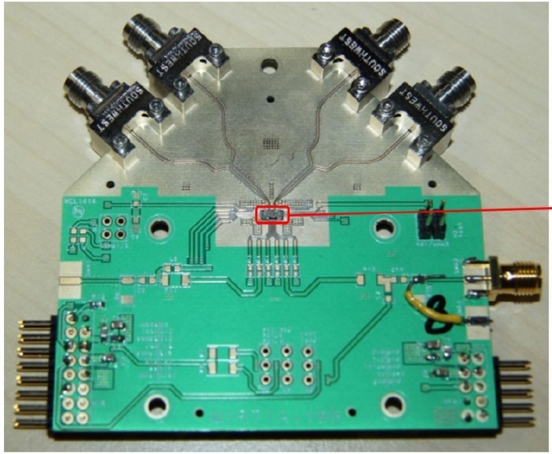
Si device layer: 400 nm thick

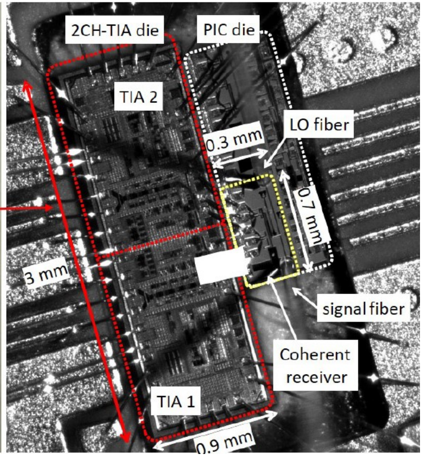
Etch step: 180 nm

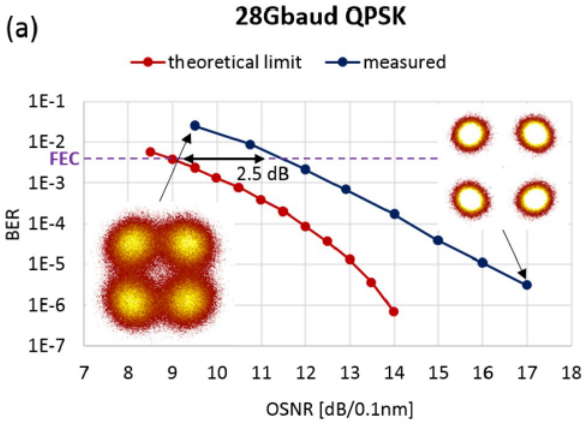


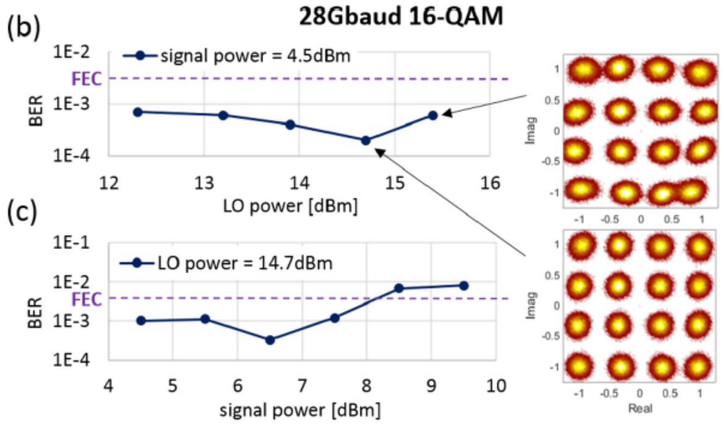
III-V-ON-SI ICR ON THE IMEC ISIPP25G/50G PLATFORM



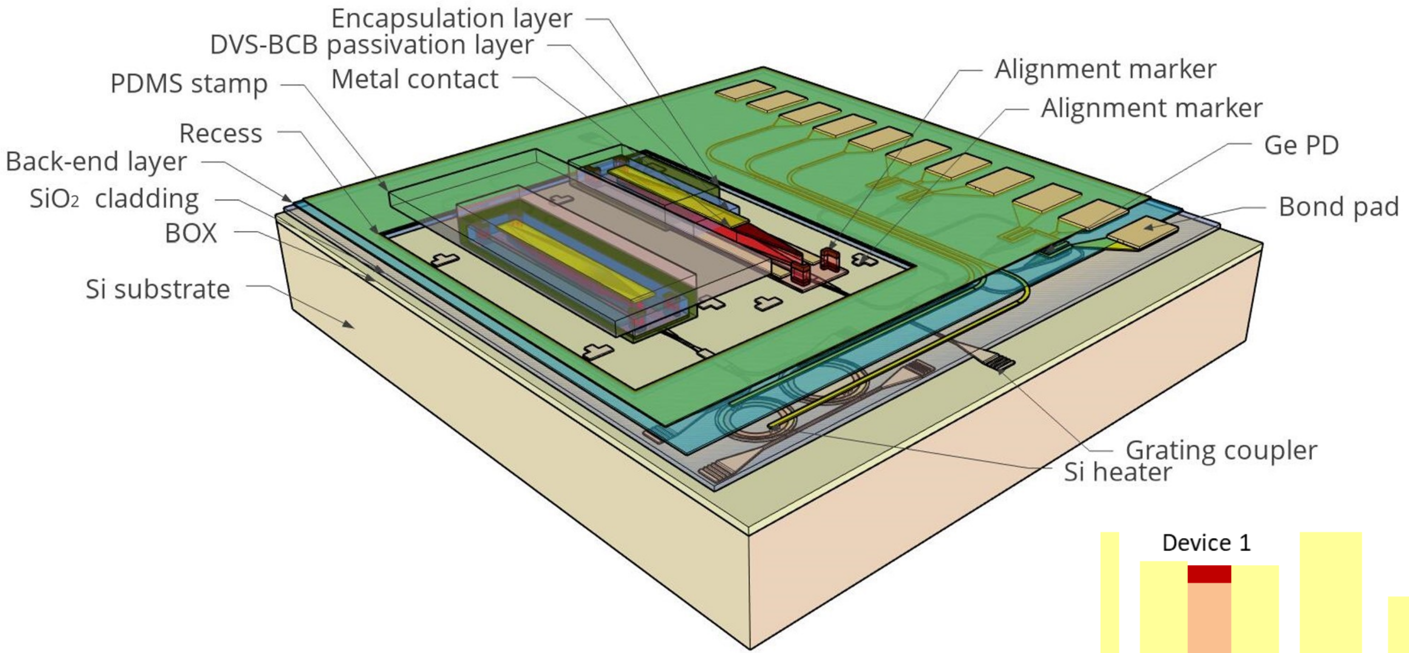


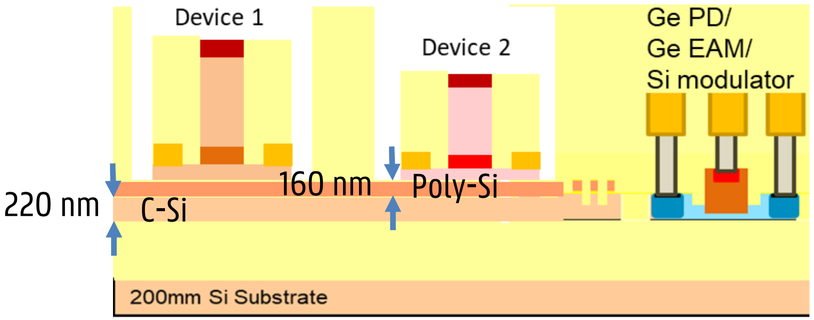




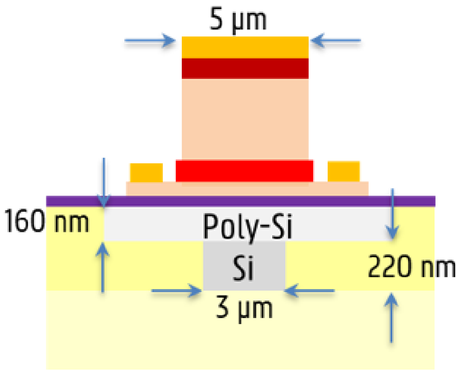


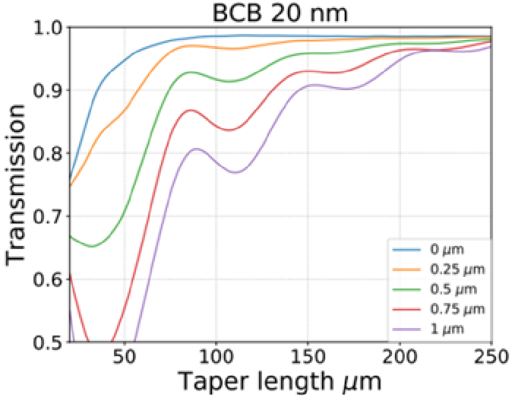
III-V-on-Si ICR on the imec iSiPP25G/50G platform

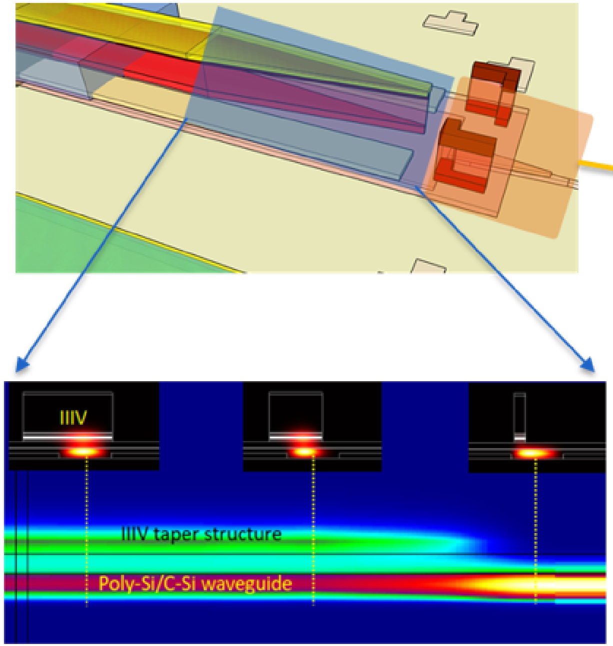




ALIGNMENT TOLERANT III-V/SI TAPER STRUCTURE

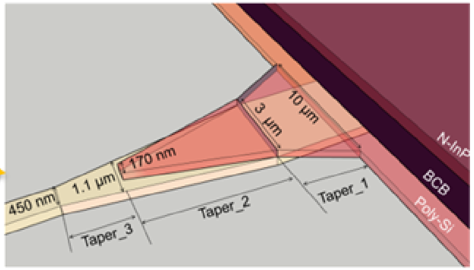


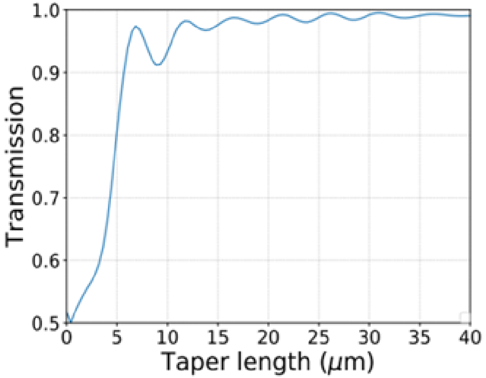




Si/poly-Si/n-InP to SOA waveguide

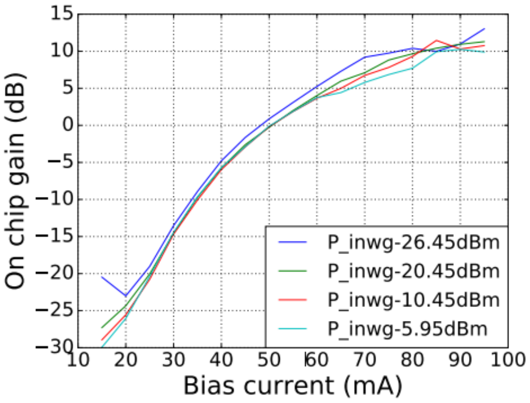
Si/poly-Si/n-InP to Si

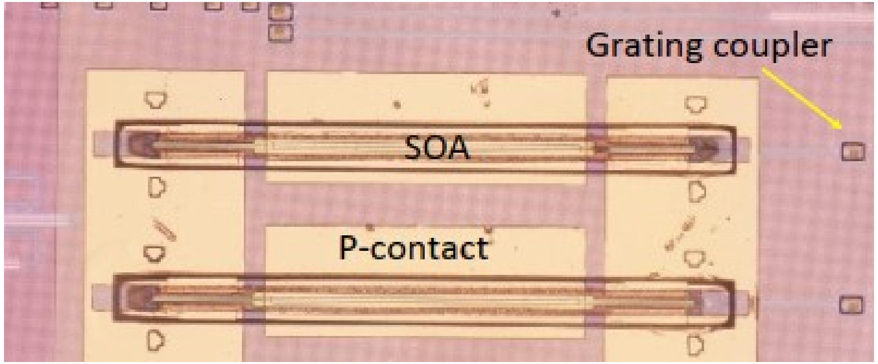


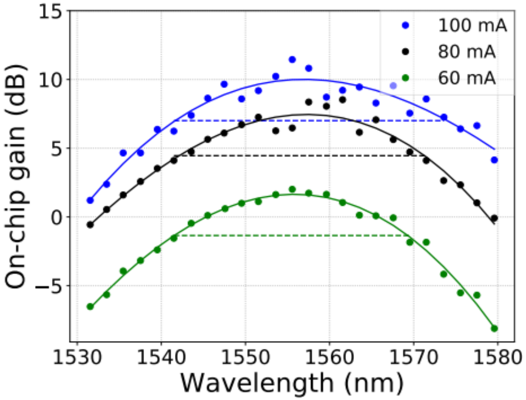


Transfer-printed SOAs on the imec iSiPP50G platform

Spray coated BCB
SOA length: ~1 mm
Small signal gain: 10dB @ 100mA
3dB gain bandwidth: 35 nm @100 mA







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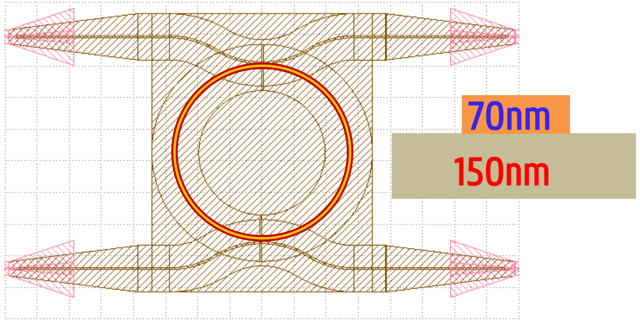
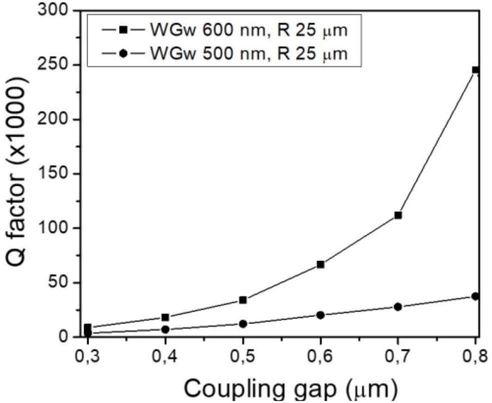
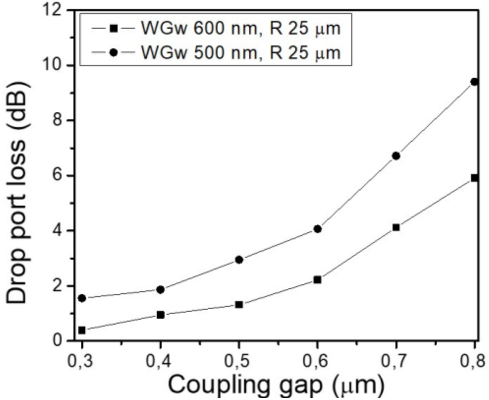
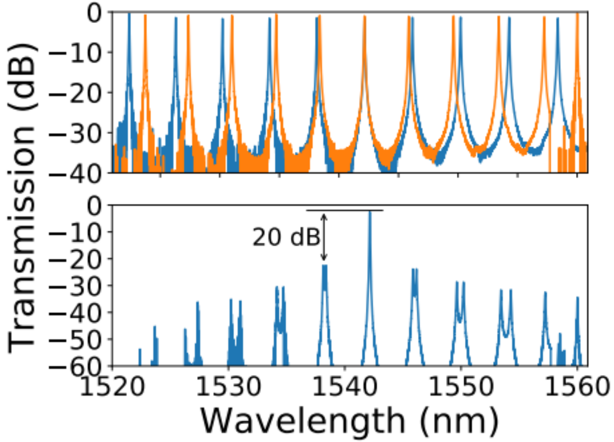
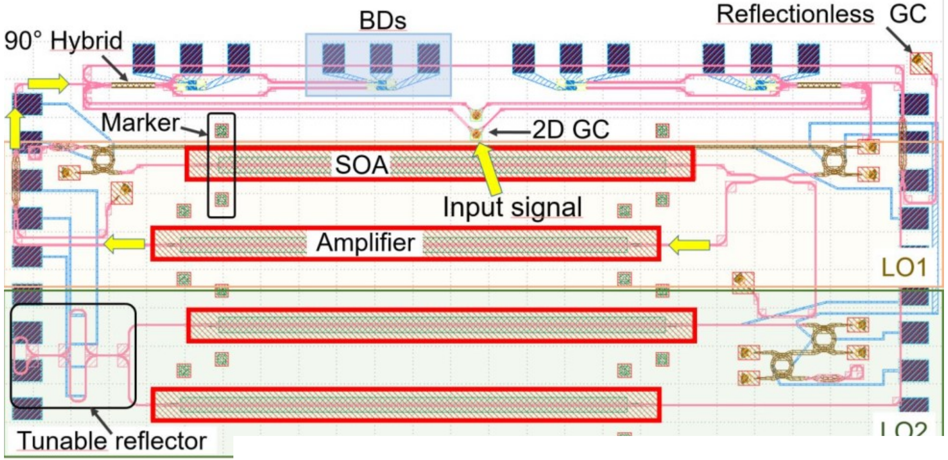
ICR DESIGNS ON THE IMEC ISIPP50G PLATFORM











We are ready for the next step!

What did I do in my PhD years?

1. Transfer-printed Fiber-To-The-Home (FTTH) transceivers
    1. Transfer printing O-band photodiodes
    2. Transfer-printed DFB lasers
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What is next:

- Complex C-band III-V/Si PICs based on iSIPP50G
- Move to O-band with InAs/GaAs QD structures
- Integration of other materials / on other photonic platforms


Thank you

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FACULTY OF ENGINEERING AND ARCHITECTURE

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