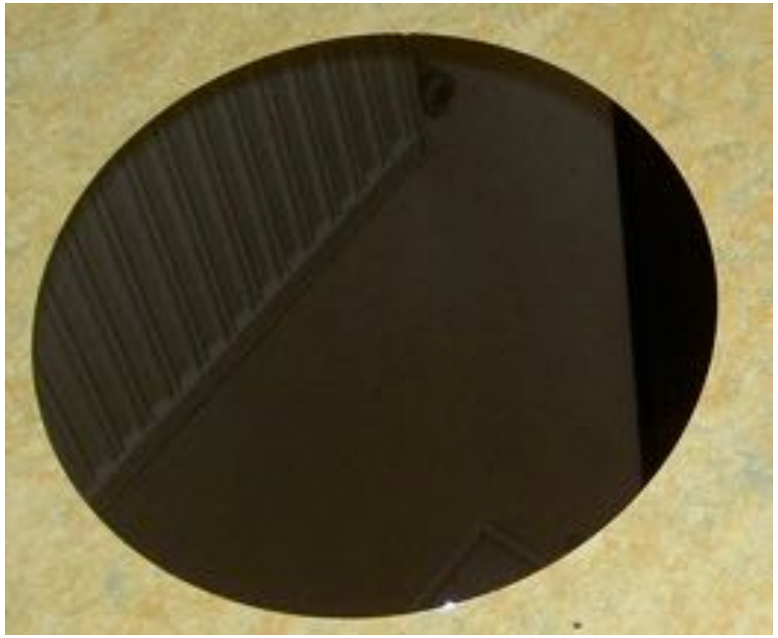
Silicon Photonics for Coherent Applications

C. Doerr

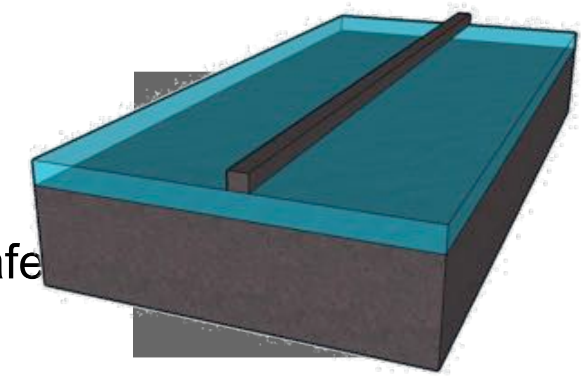
Silicon photonics

SiPh

Boule

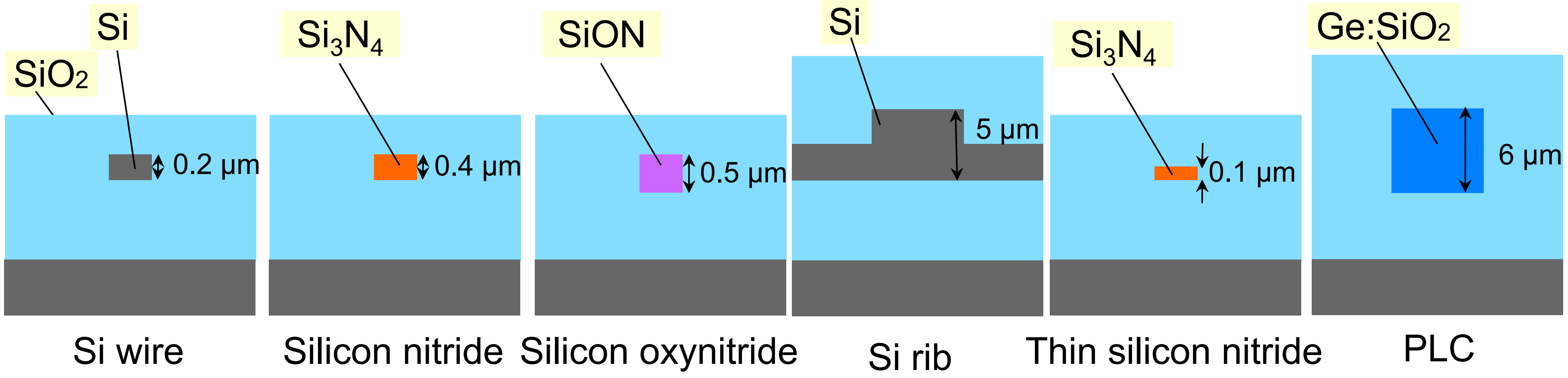


12” (300 mm) wafer



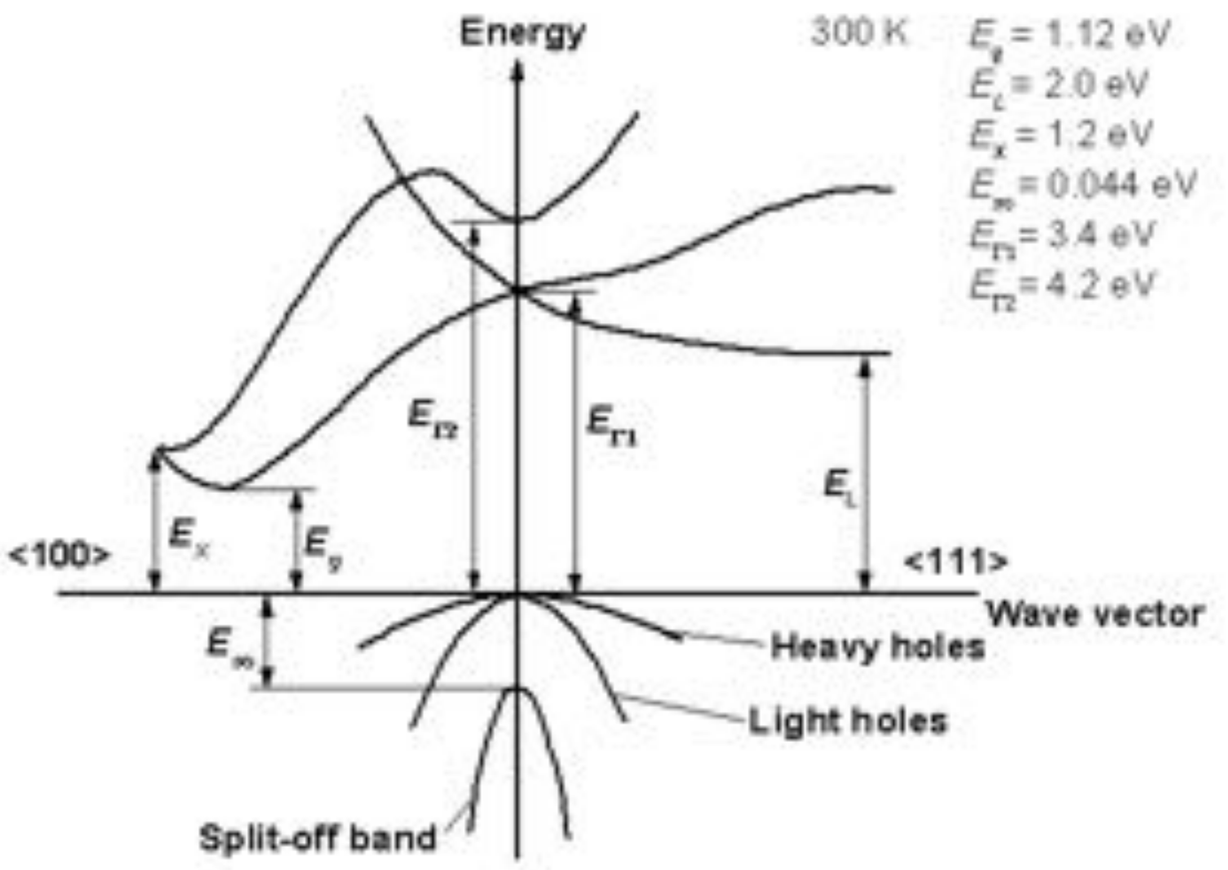
Silicon on insulator (SOI) wafe

SiPh family



Si
SiO2
0.2 µm
Si3N4
0.4 µm
SiON
0.5 µm
Si
5 µm
Si3N4
0.1 µm
Ge:SiO2
6 µm
Si wire
Silicon nitride
Silicon oxynitride
Si rib
Thin silicon nitride
PLC

Band structure for Si



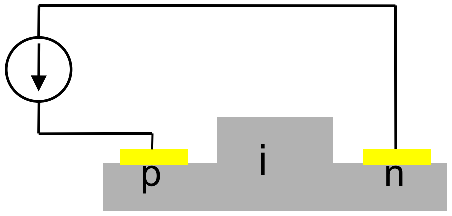
Electro-refraction/absorption in Si

Refraction $$\Delta n_r = -8.8 \times 10^{-22} N_e - 8.5 \times 10^{-18} N_h^{0.8}$$

Absorption $$\Delta n_i = 1.05 \times 10^{-22} N_e + 7.4 \times 10^{-23} N_h$$

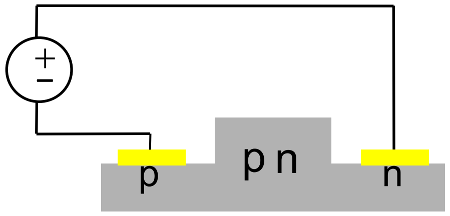
N_e = free electron density in cm^{-3}
N_h = free hole density in cm^{-3}

Electro-optic modulation in Si/Ge



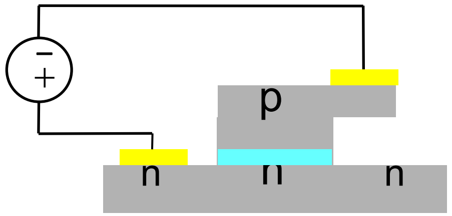
Carrier injection

Causes both phase and magnitude change (can be used as a VOA)
Slow



Carrier depletion

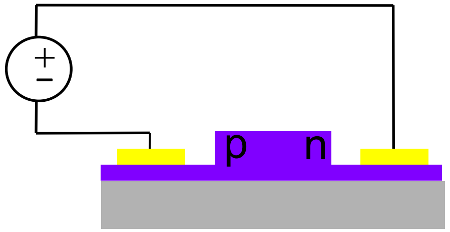
Fast
Weak (typ 2 V-cm)



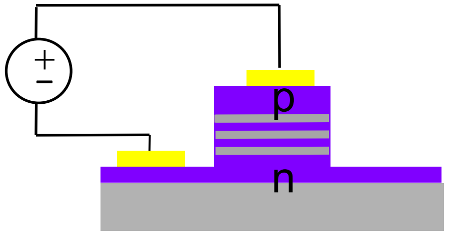
Metal-oxide-semiconductor

Strong (typ 0.2 V-cm)
Fast (but high capacitance)
Lossy

No Pockels effect or QCSE exist in Si

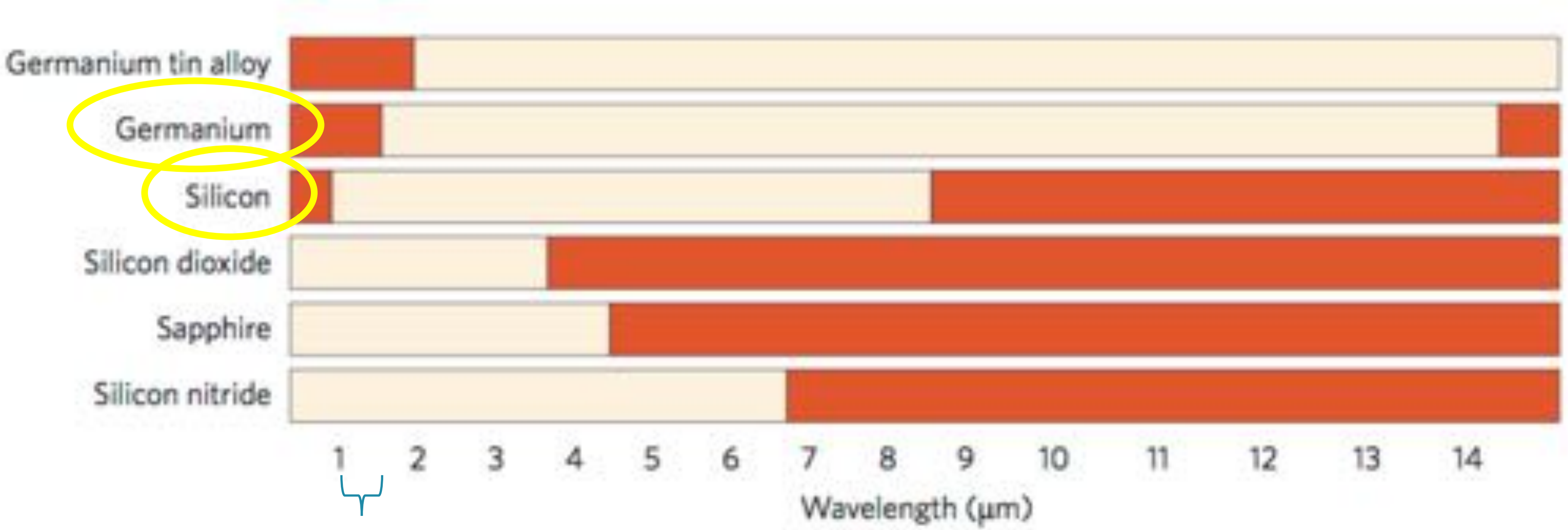


SiGe bulk



SiGe QW

Material transparency

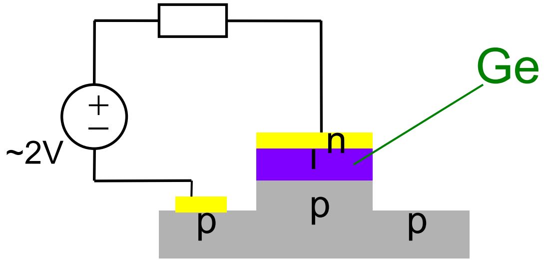


Transmit through Si and receive in Ge

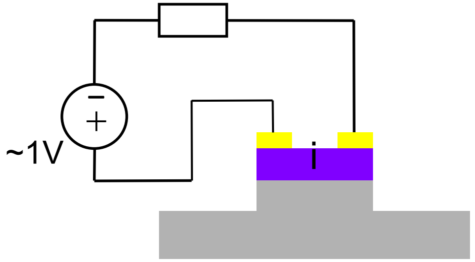
R. Soref, Nature Photonics, 2010.

Photodetectors in Si/Ge

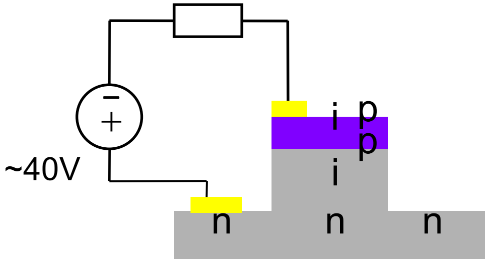
p-i-n



MSM



APD

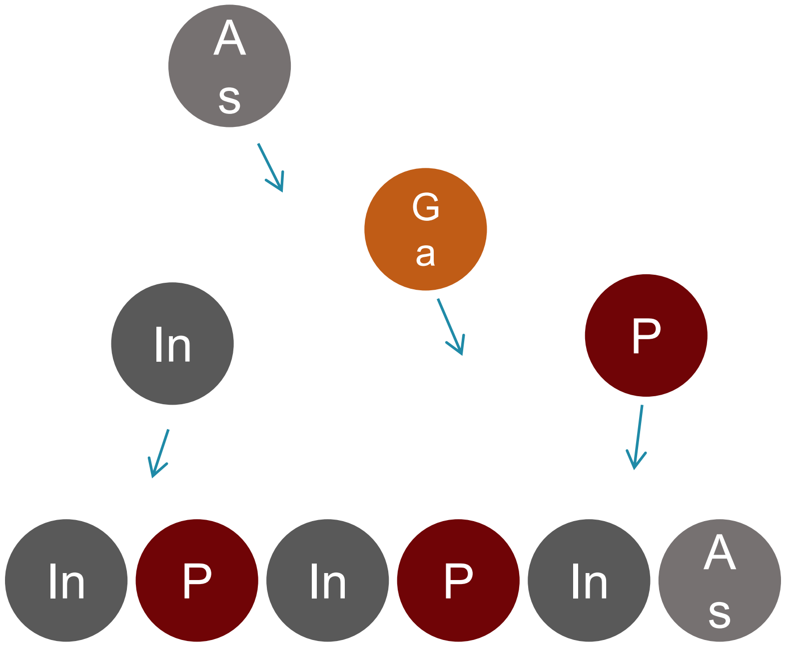


Main advantage of silicon photonics

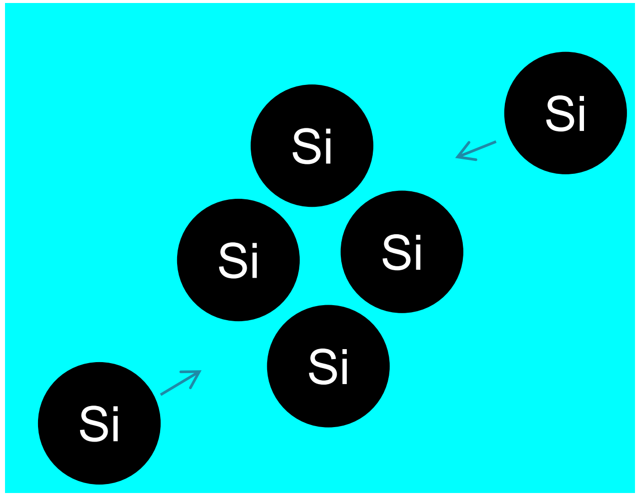
- Ability to integrate many elements with very high yield

- Not
  - Die cost savings
  - Monolithic CMOS integration

Why SiPh high yield compared to InP?



4 different atom types, dry growth



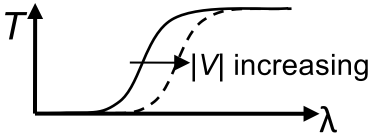
Single atom type, wet growth

InP – SiPh comparison

InP

- Expensive material
  - In is scarce
- Medium yield
  - W.g. material from epitaxy

- Small footprint
  - High index contrast in 1D
- Efficient laser
- No good native oxide
- Low dark current



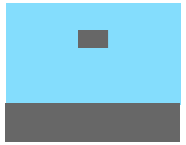
- Small wafers
  - Brittle material
- Modulator temp. sensitive
- Narrow wavelength range
- Not flip-chip-able

SiPh

- Cheap material
  - 27% Earth's crust is Si

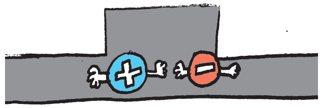
- High yield
  - W.g. material from original boule

- Extremely small footprint
  - High index contrast in 2D



- No native laser
- Excellent native oxide
- Medium dark current
- Large wafers
  - Strong material

- Modulator temp. insens.
- Large wavelength range
- Flip-chip-able



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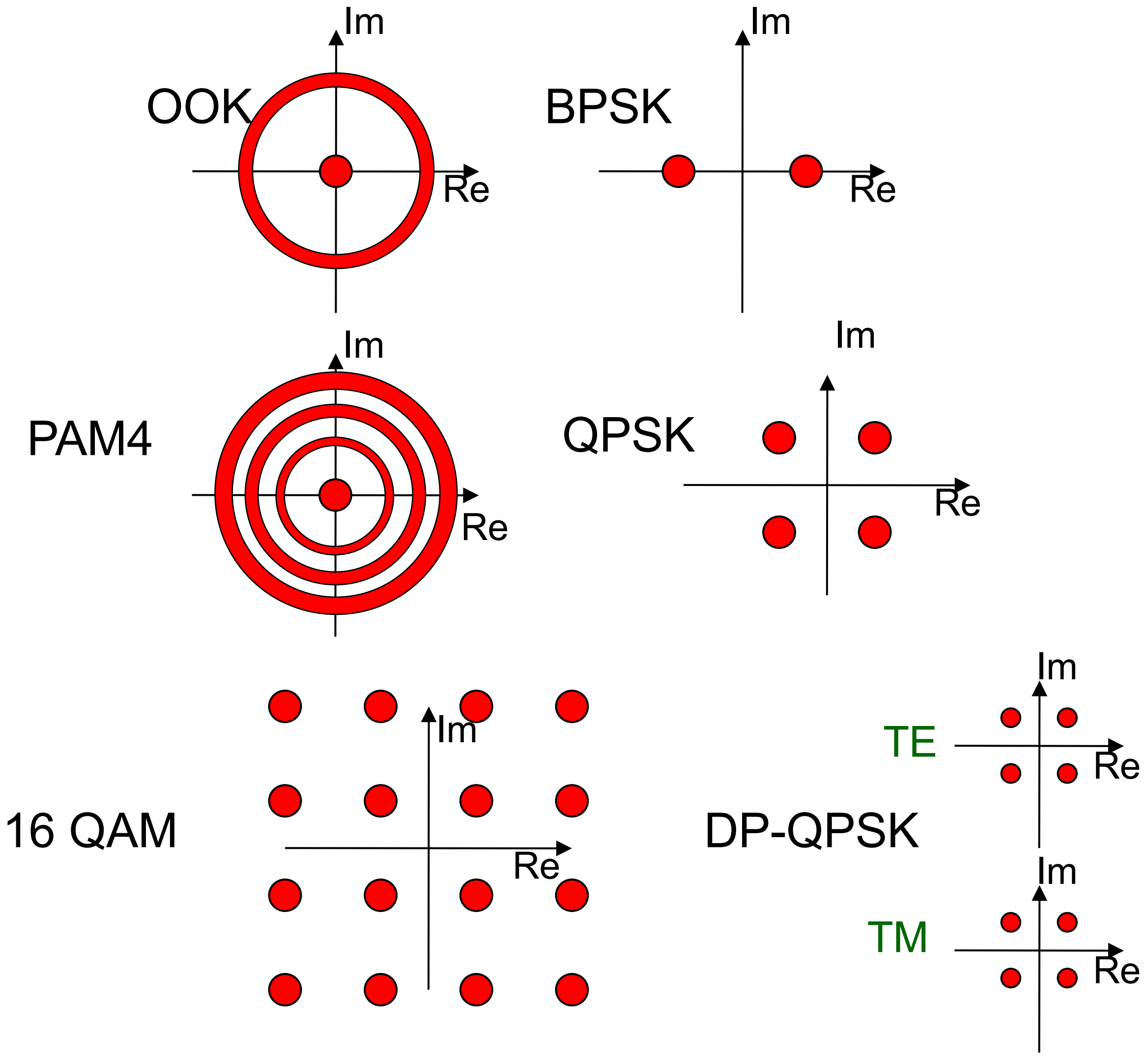
Coherent systems

Advanced modulation formats for optical communication



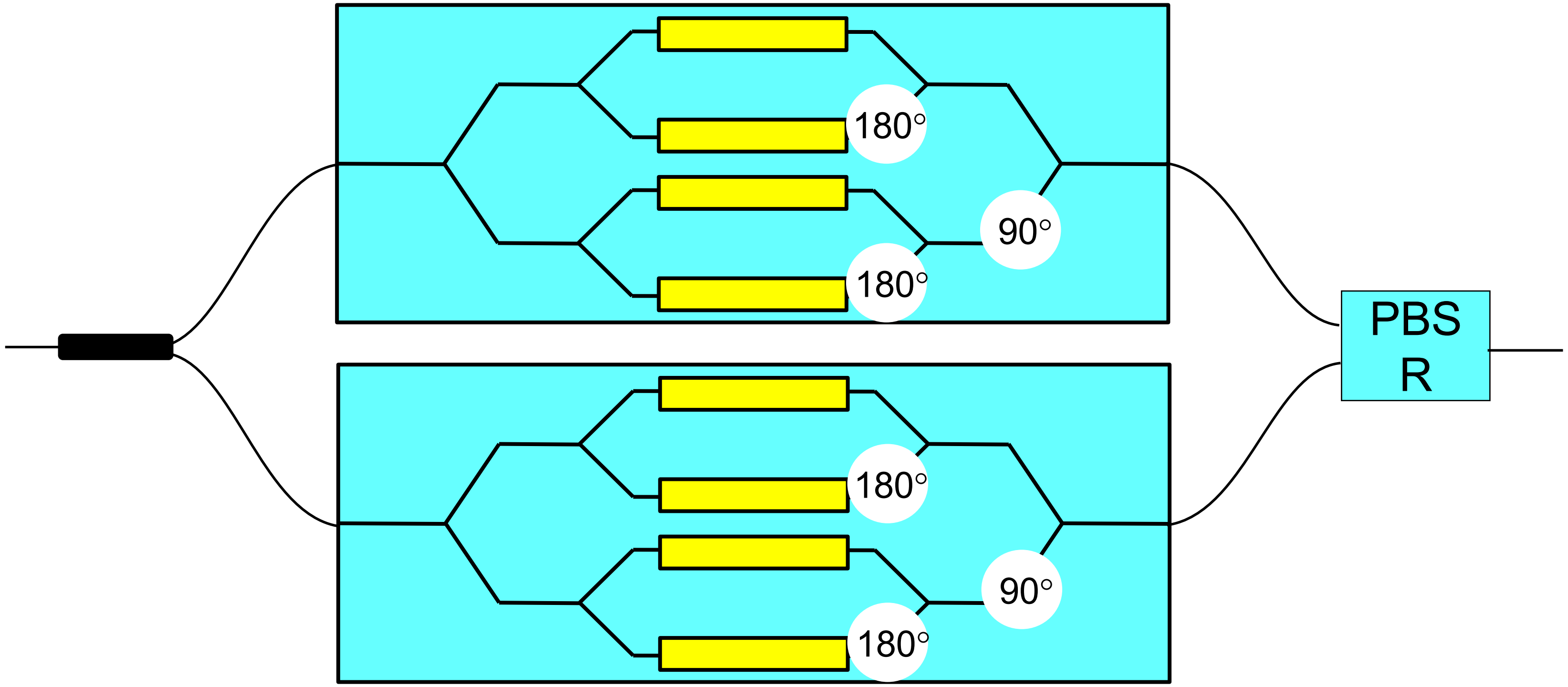
b/baud = 1

b/baud = 2

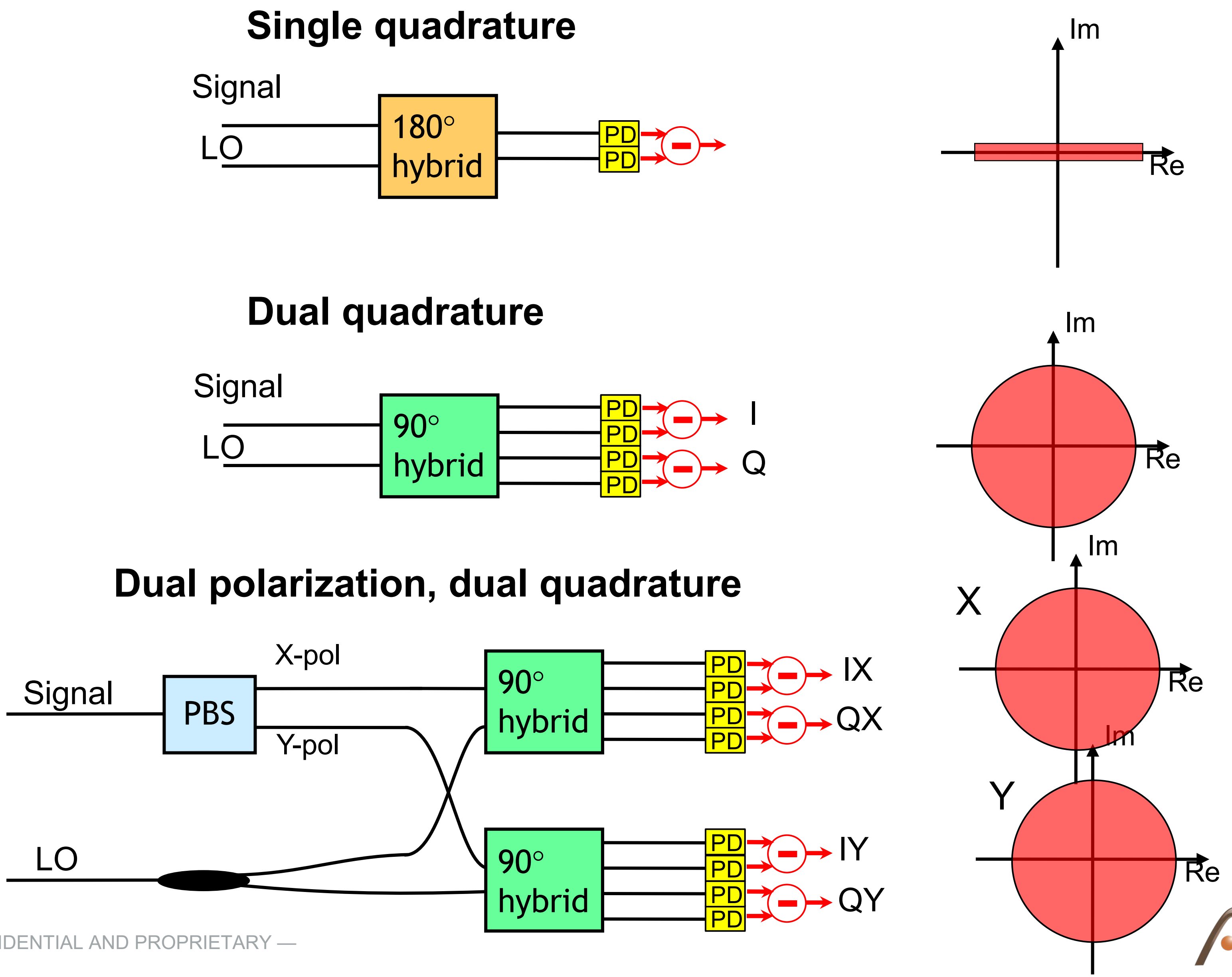
b/baud = 4

OOK = on-off keying
BPSK = binary phase-shift keying
QPSK = quadrature phase-shift keying
QAM = quadrature amplitude modulation
DP = dual polarization

Advanced modulation format Tx



Coherent reception



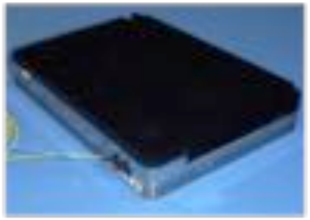
Benefits of coherent

- High spectral efficiency
- High sensitivity
- Electronic compensation of impairments
- No Rx optical filter required
- Low cost per bit

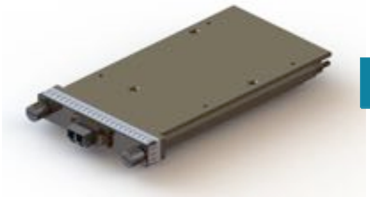
Coherent module evolution

2009
Line card, >100W

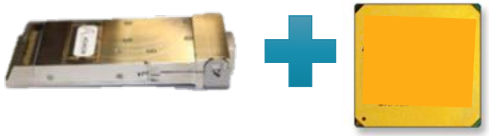
2012
MSA, 70W



2014
D-CFP, 28W



2016
A-CFP2, 12W (+DSP)



2017
D-CFP2, 14W

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Size and power reduction enabled by
- Smaller CMOS node size
- Optical integration

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CMOS node size reduction

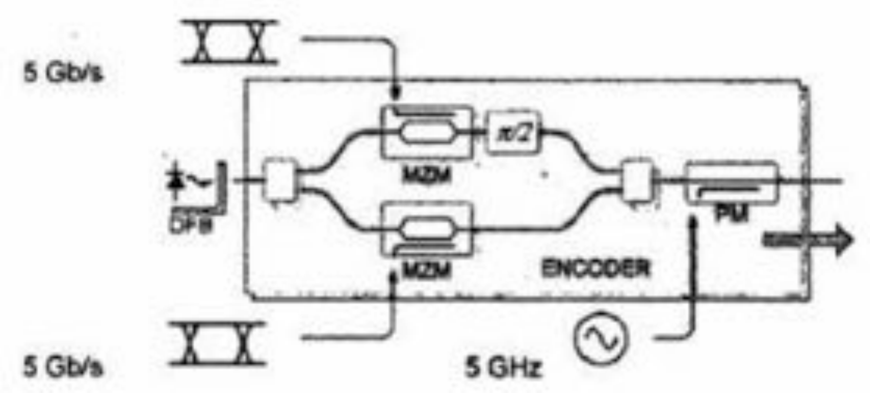
Semiconductor manufacturing processes

- 10 µm – 1971
- 6 µm – 1974
- 3 µm – 1977
- 1.5 µm – 1982
- 1 µm – 1985
- 800 nm – 1989
- 600 nm – 1994
- 350 nm – 1995
- 250 nm – 1997
- 180 nm – 1999
- 130 nm – 2001
- 90 nm – 2004
- 65 nm – 2006
- 45 nm – 2008
- 32 nm – 2010
- 22 nm – 2012
- **14 nm** – 2014
- 10 nm – 2016
- 7 nm – 2018
- 5 nm – 2020

Coherent optics

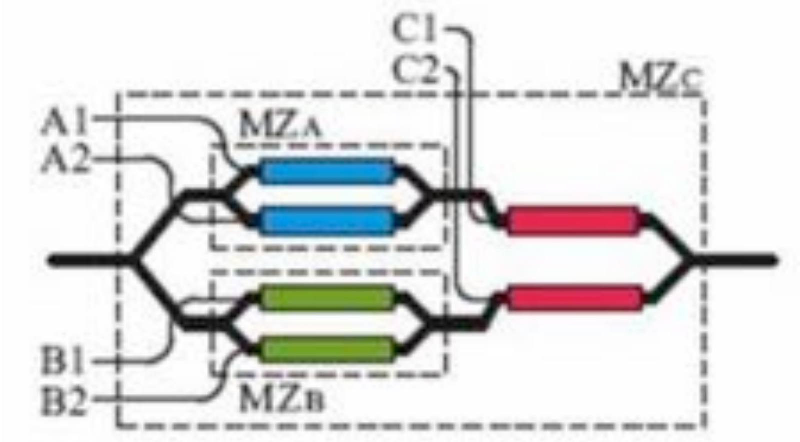
Coherent optics evolution

Early advanced format modulators



GaAs

R. Griffin, et al., paper FP6, OFC 2003.



$LiNbO_3$

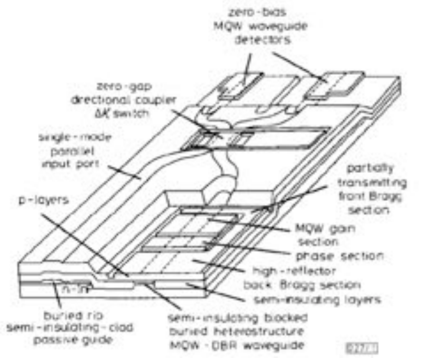
T. Kawanishi, et al., paper OWH5, OFC 2007.

Early coherent receivers

1 pol., 1 quad.

T. L. Koch, et al., Electron. Lett., vol. 25, pp. 1621-1622, 1989.

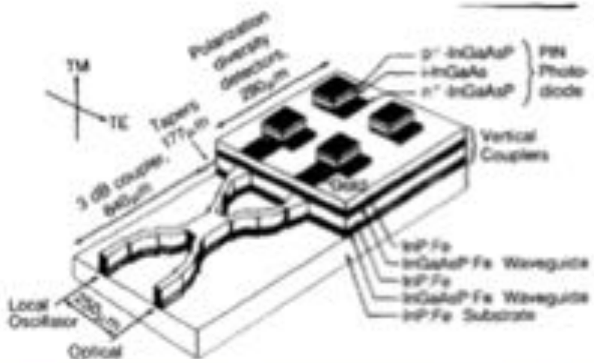
Also, H. Takeuchi, et al., IEEE Photon. Tech. Lett., vol. 1, pp. 398-400, 1989.



InP

2 pol., 1 quad.

R. J. Deri, et al., IEEE Photon. Tech. Lett., p. 1238, 1992.



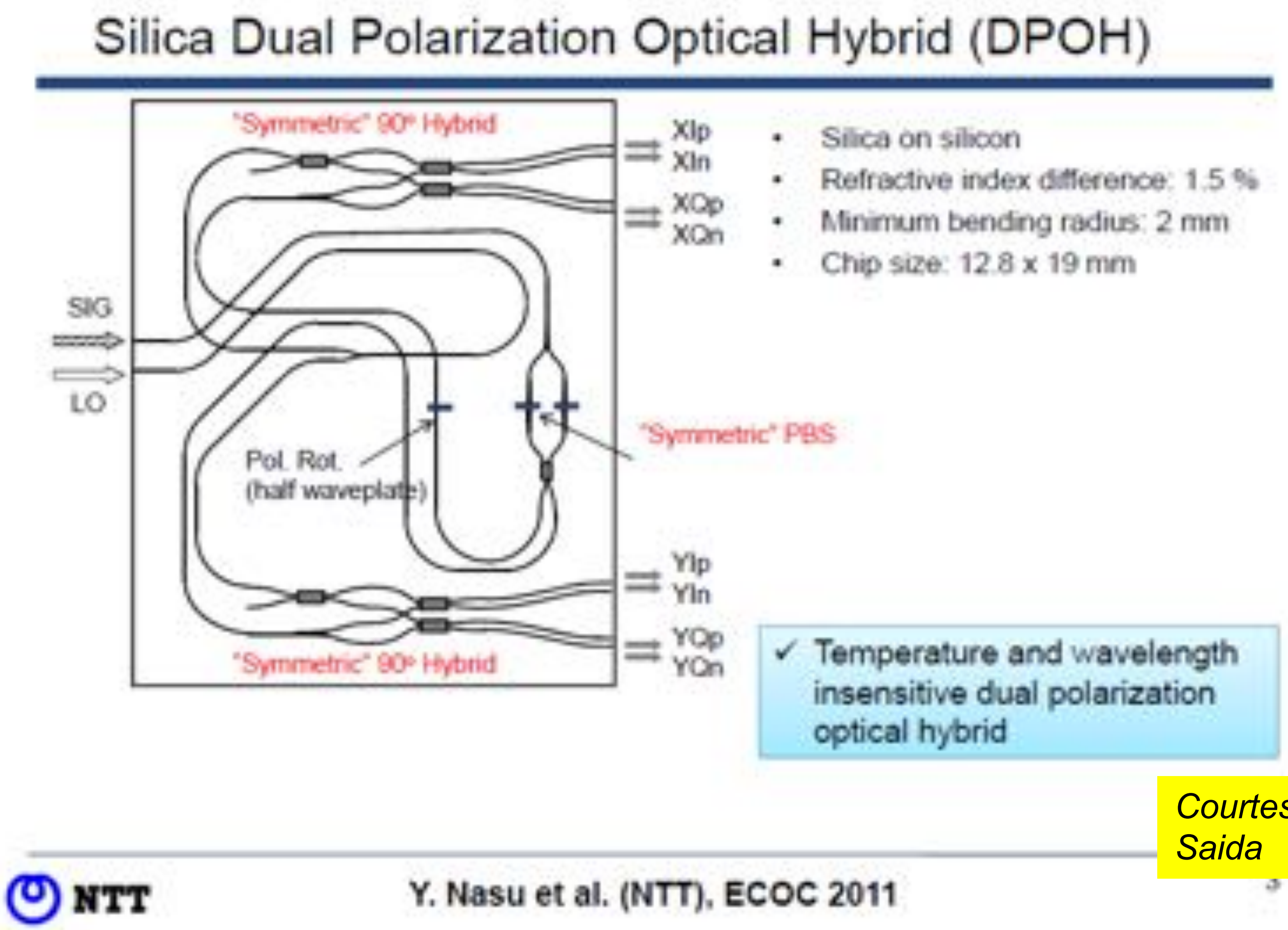
InP

1 pol., 2 quad.

H.-G. Bach, et al., OFC, OMK5, 2009.

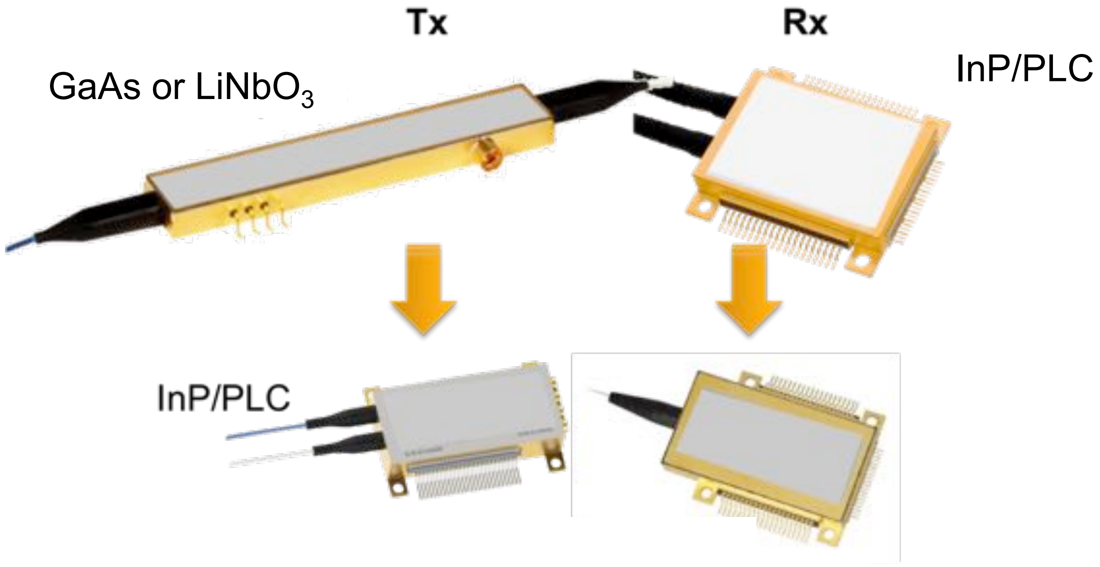
InP

PLC coherent receiver

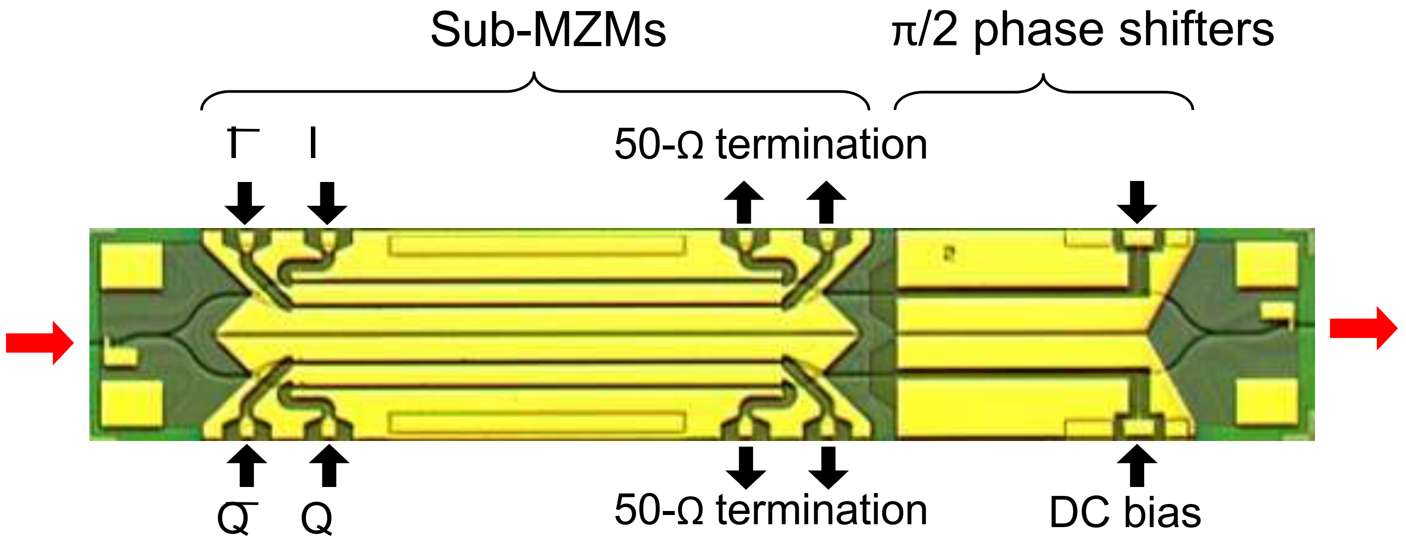


Courtesy of T. Saida

Coherent optics evolution



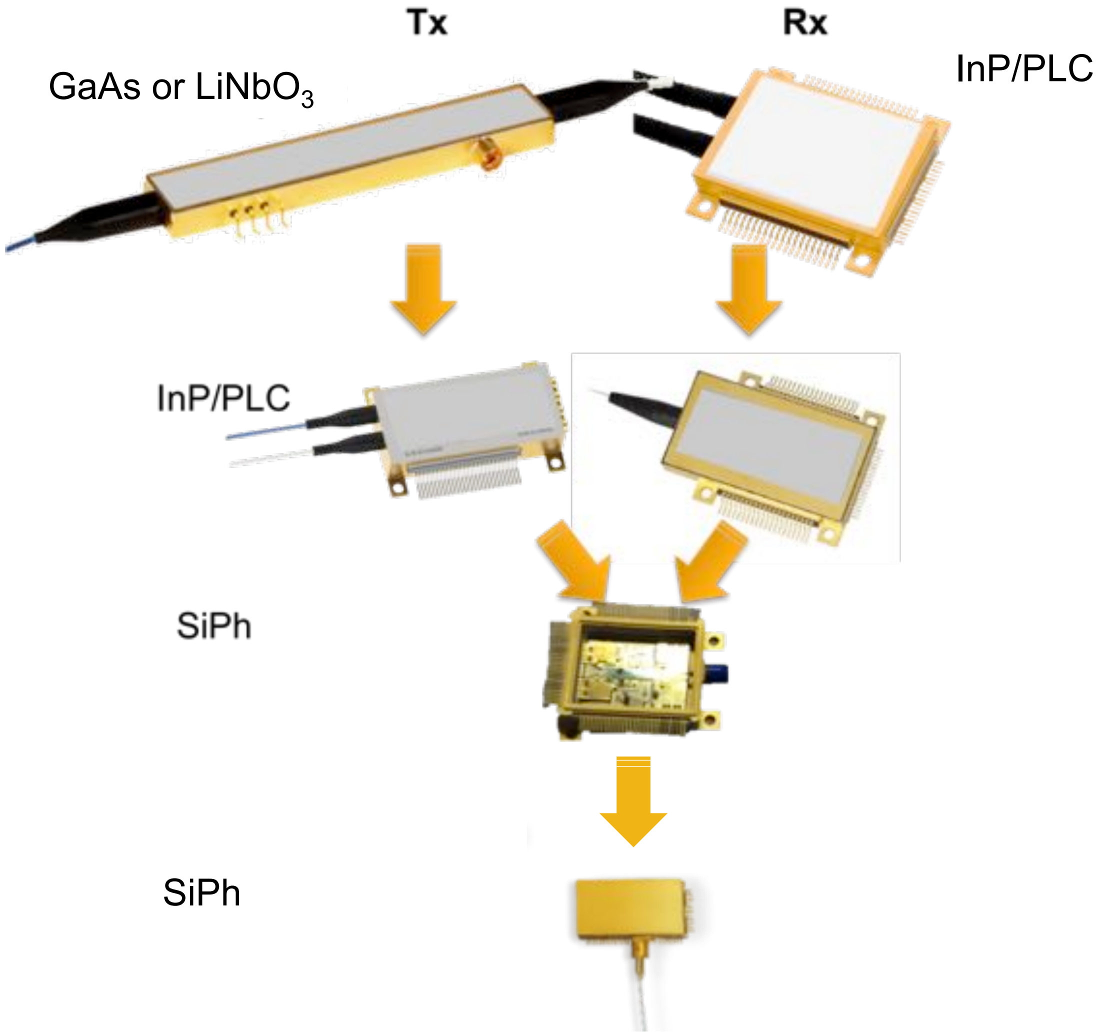
InP advanced format modulator



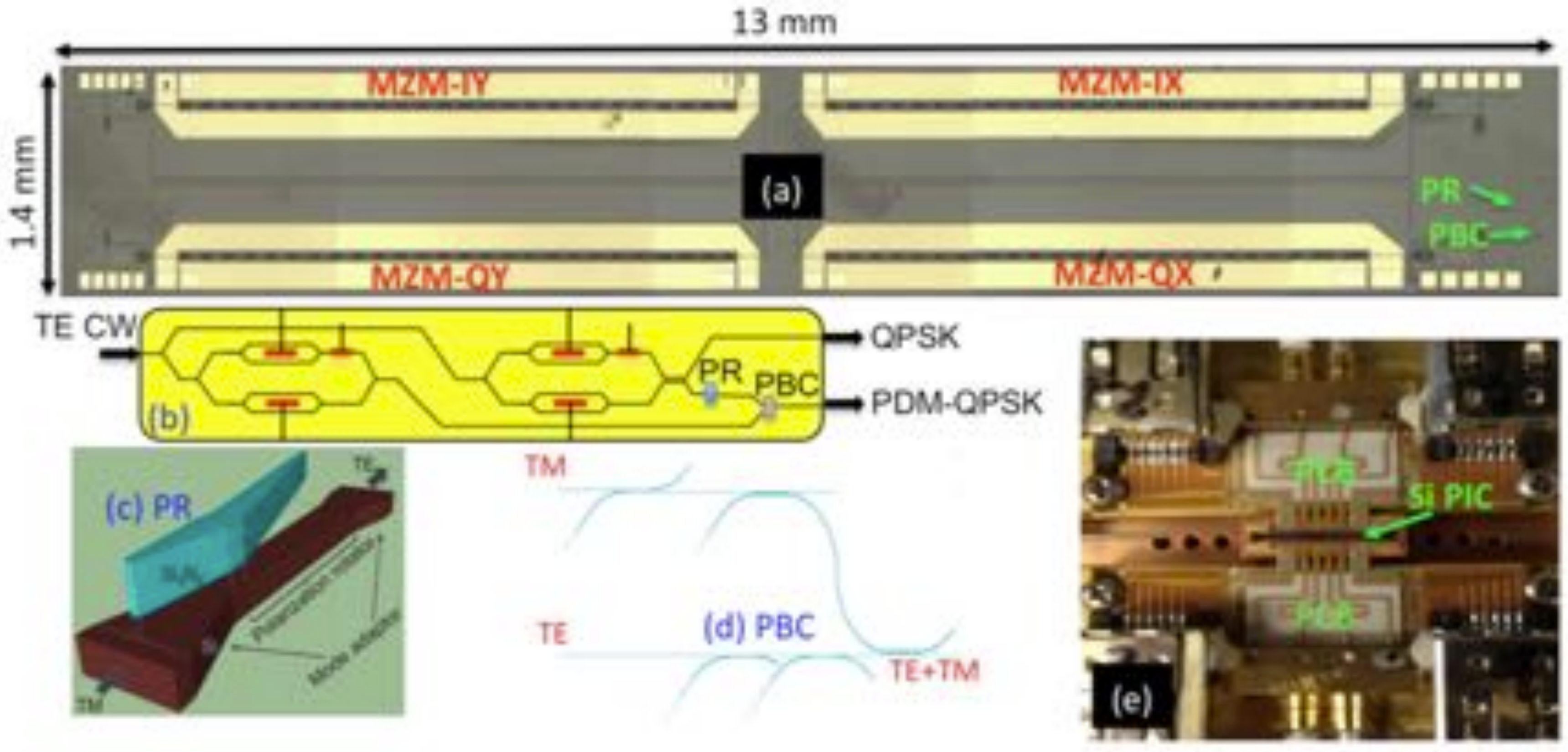
N. Kikuchi, ECOC, 10.3.1, 2007.

26

Coherent optics evolution

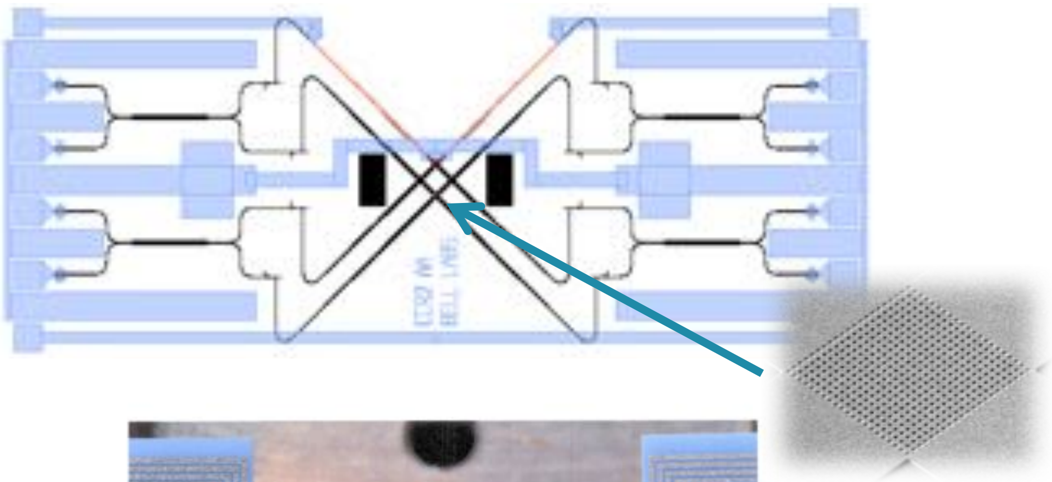


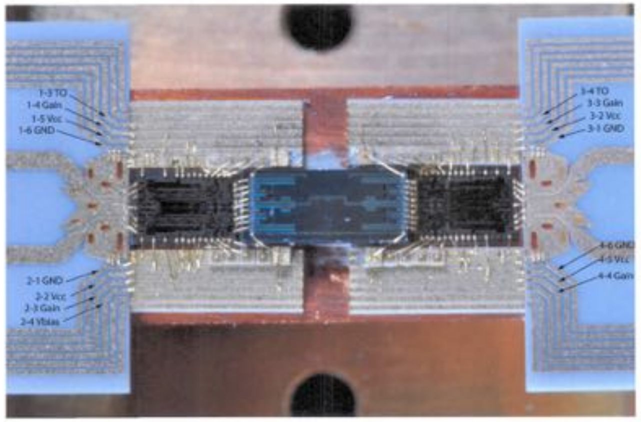
SiPh advanced format modulator



P. Dong, L. Chen, et al., Opt. Exp., 2012.

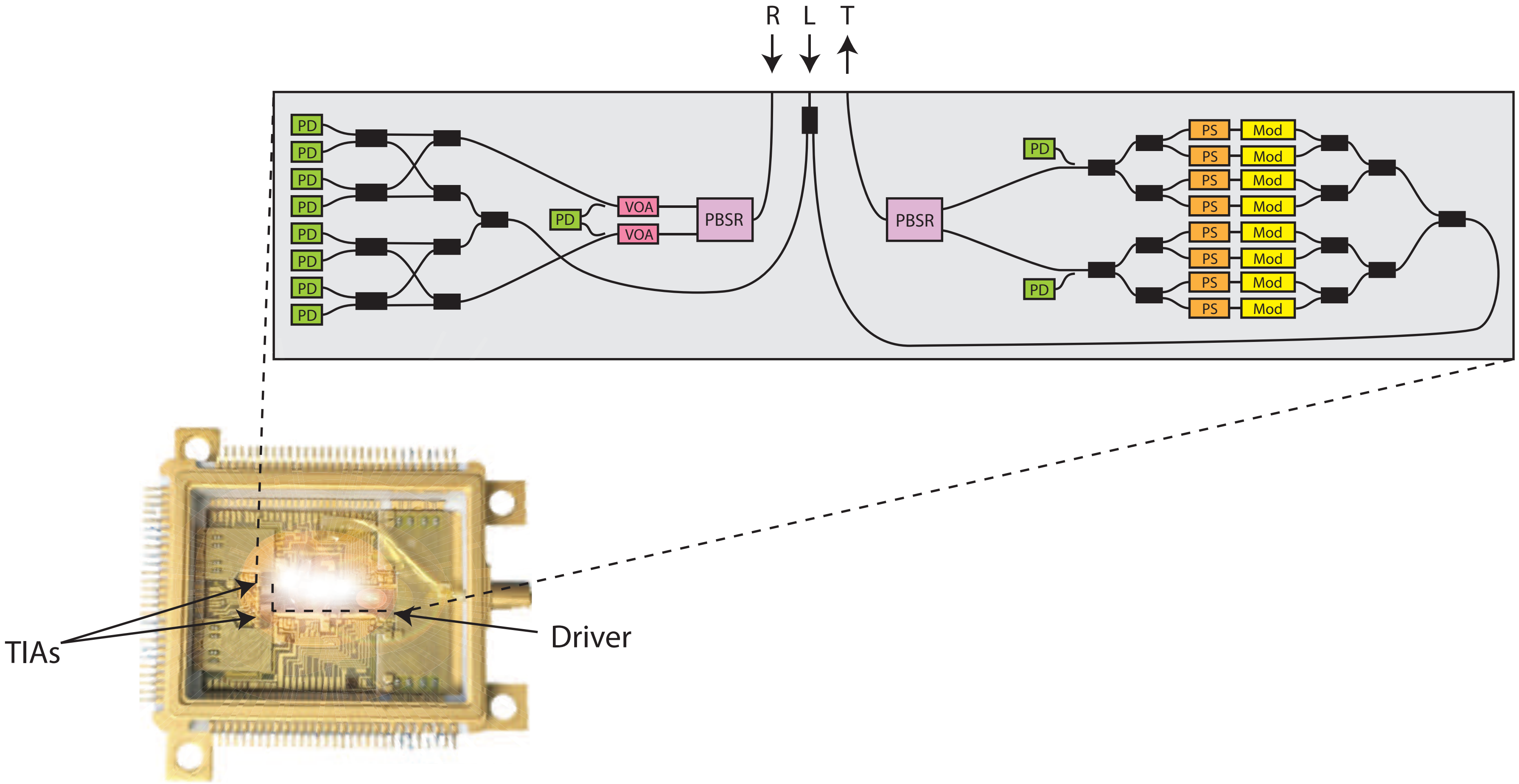
SiPh coherent receivers





C. R. Doerr, et al., J. Lightwave Tech., vol. 28, pp. 520-525, 2010.
C. R. Doerr, et al., IEEE PTL, 2011.

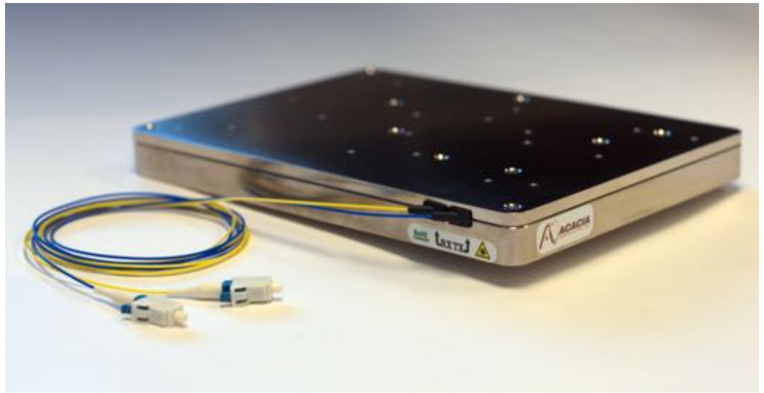
Single-chip coherent transceiver



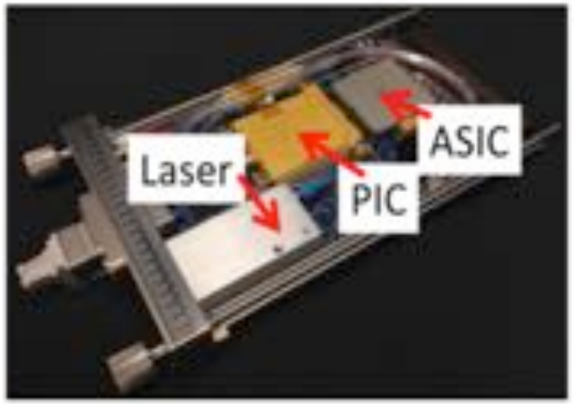
Power consumption = 4.3 W

C. Doerr, et al., OFC, Th5C.4, 2016

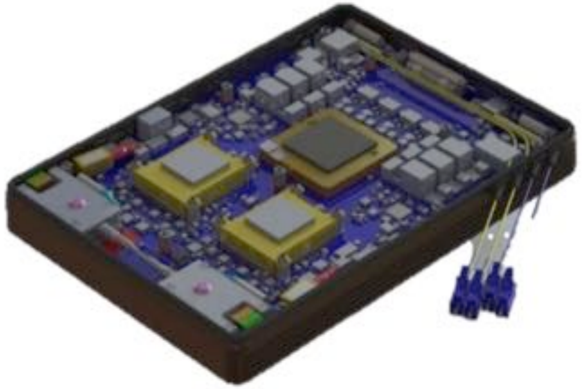
Acacia coherent modules using SiPh



100G MSA



100G CFP



Dual-carrier 400G MSA

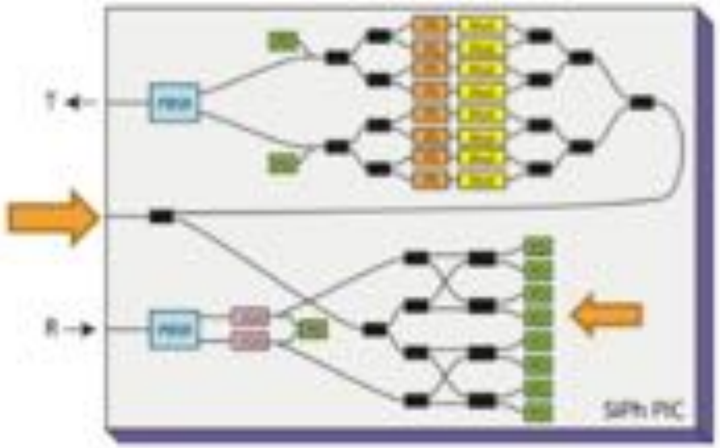
200G CFP2-ACO

200G CFP2-DCO

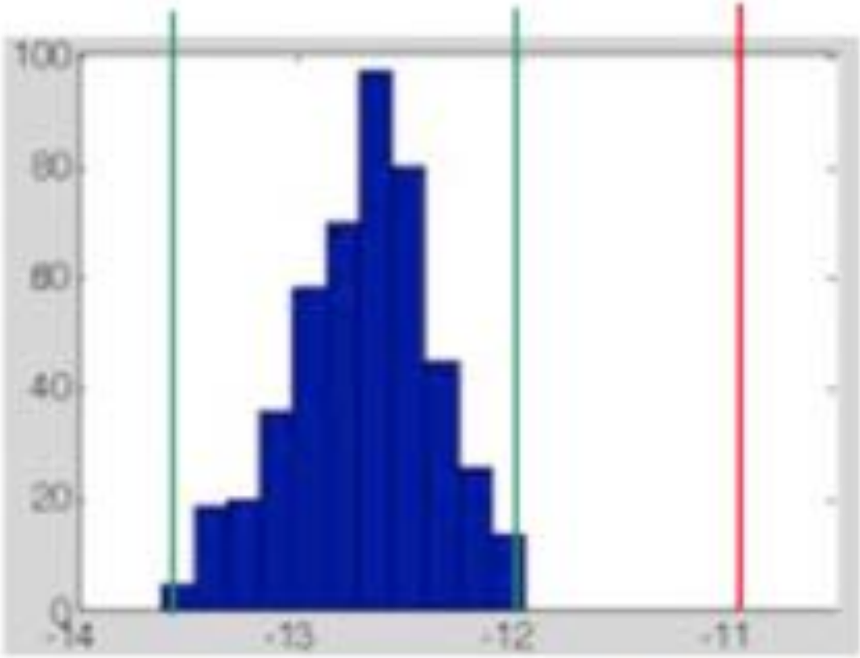
Example: Rx loss

Equivalent resp: 0.7 A/W 1 A/W
Excess loss: 2.5 dB 1.0 dB

Theoretical limit: lossless, 100% quantum efficiency (1.25 A/W)

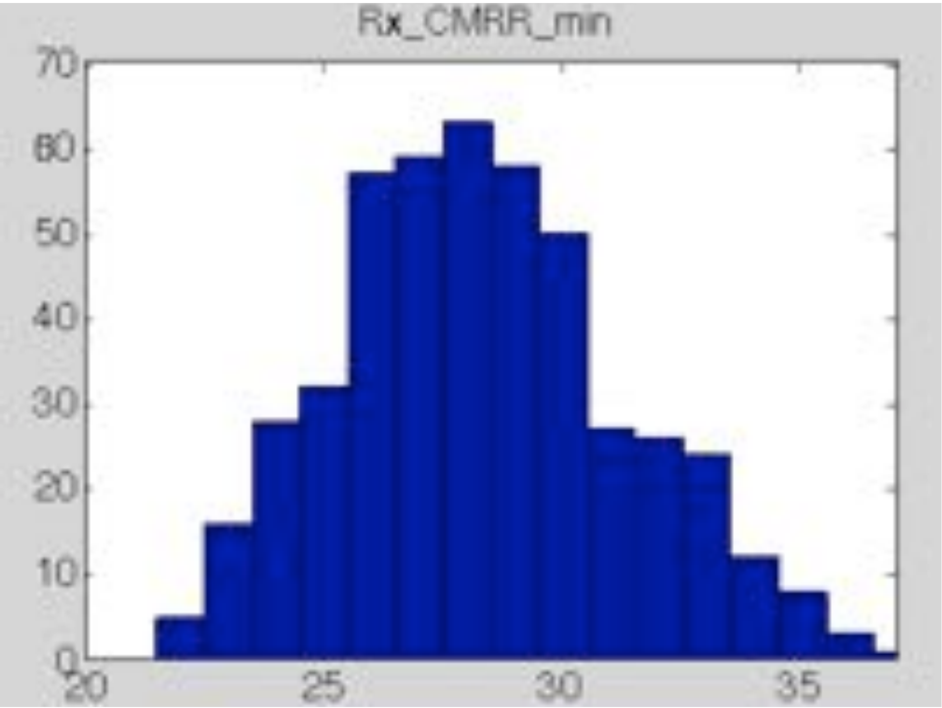


(intrinsic loss: 12 dB)



fiber to PD responsivity, A/W in dB

Example: Rx common mode rejection ratio



worst Rx CMRR per PIC, in dB scale, over C-band over 4 pairs of PDs

- CMRR determines the capability for handling multi-channel Rx without demux.
- Mean: 27 dB

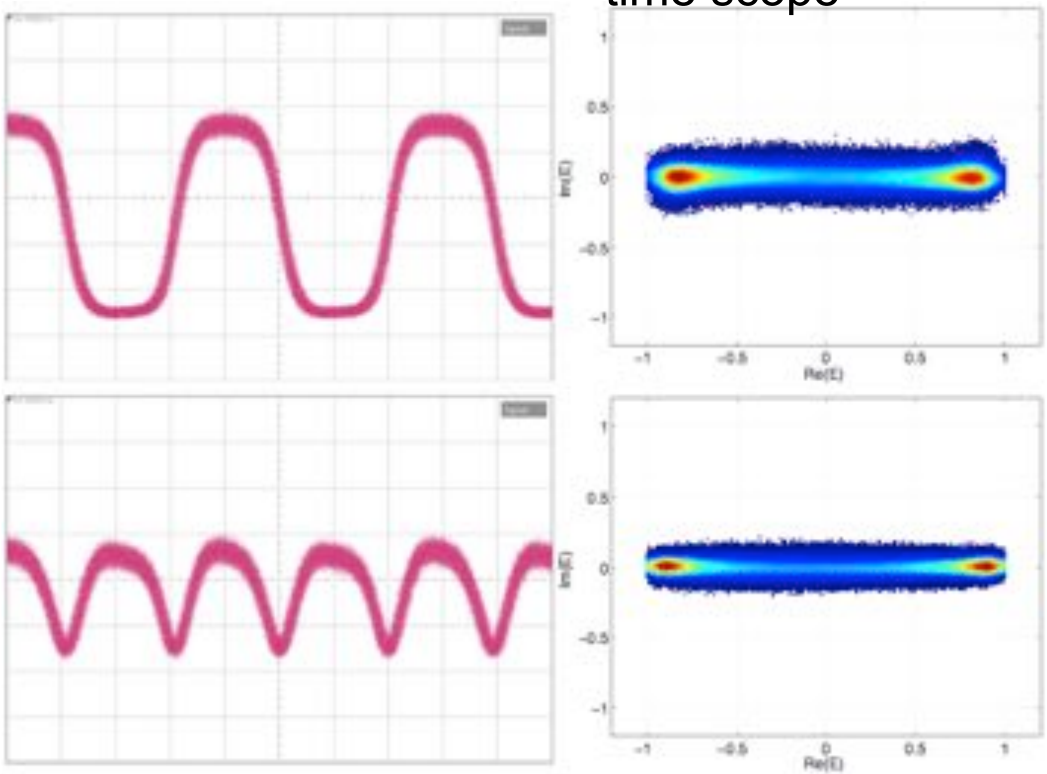
Si modulator with linear driver: improved ER and low chirp

Waveforms captured by direct detection and sampling scope

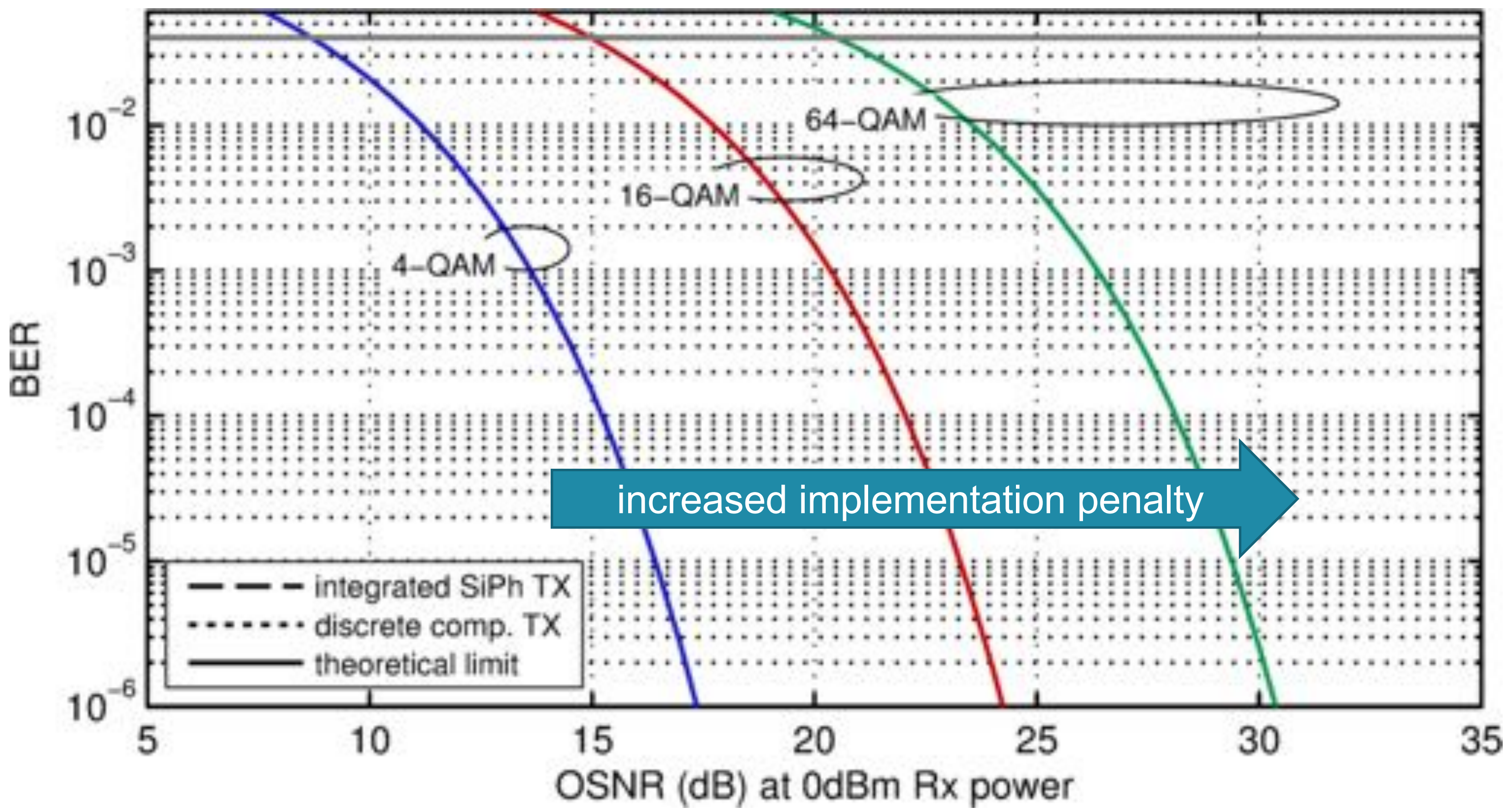
Waveforms captured by coherent detection and real-time scope

OOK

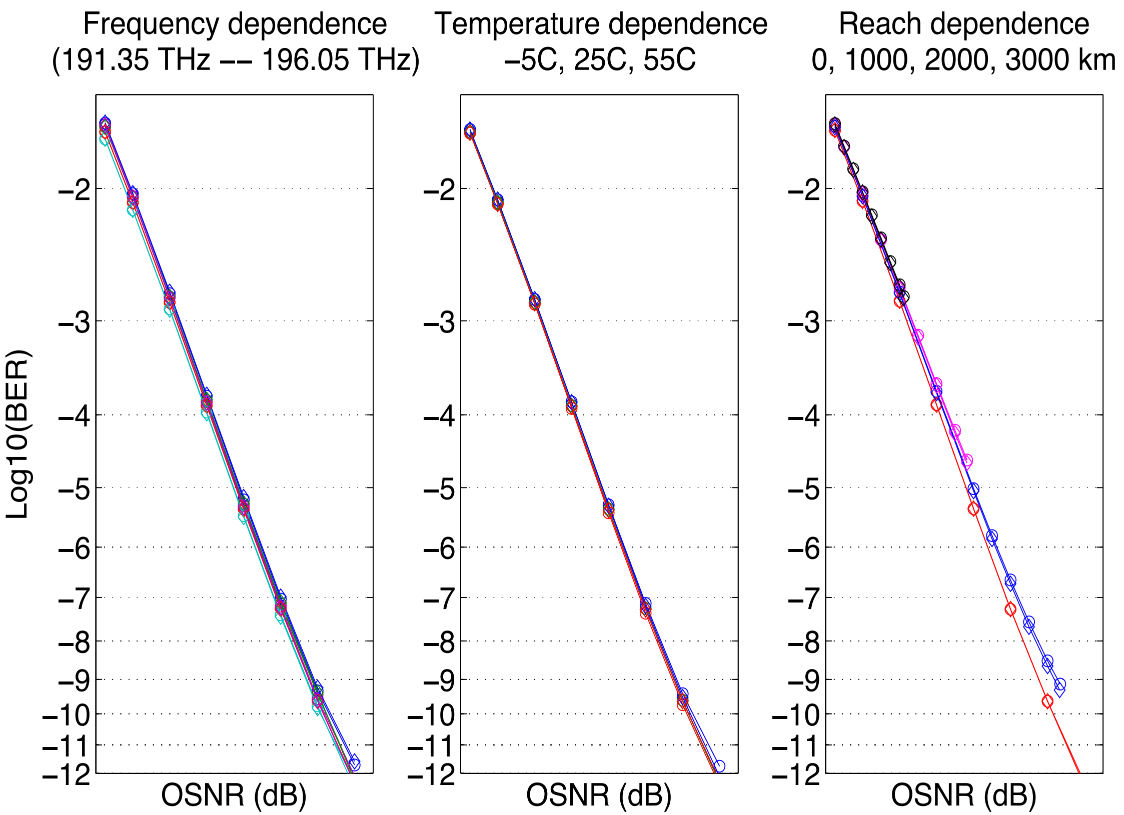
BPSK



Measured performance (30 Gbaud)

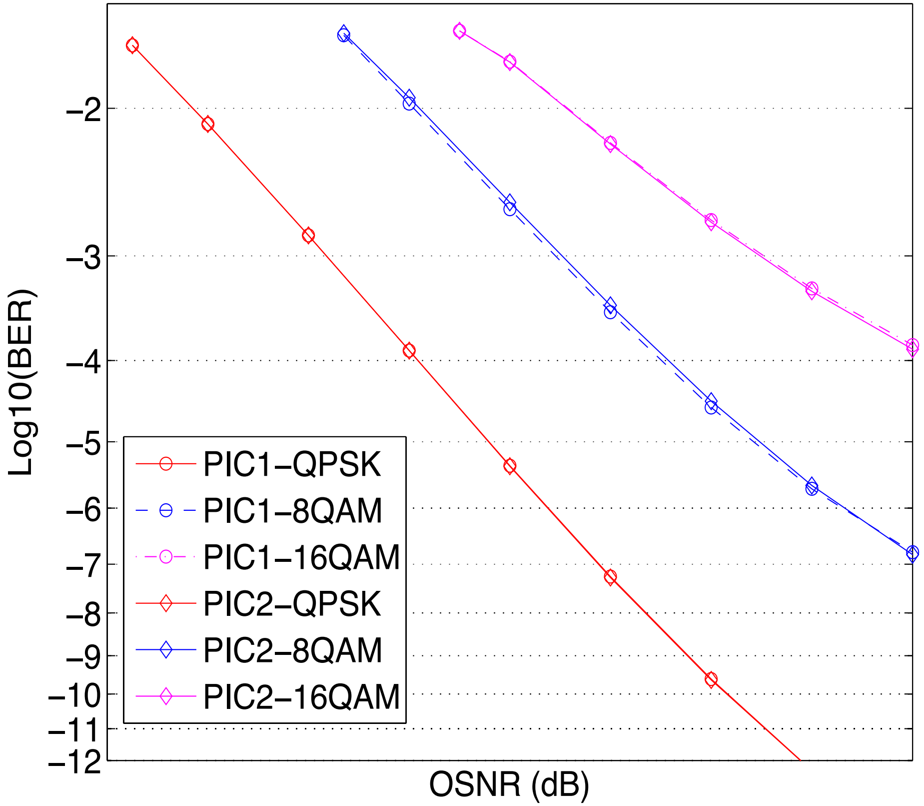


Dual-carrier MSA:
wavelength, temperature, and reach at 2 x 100G



Results of two lanes are super-imposed.

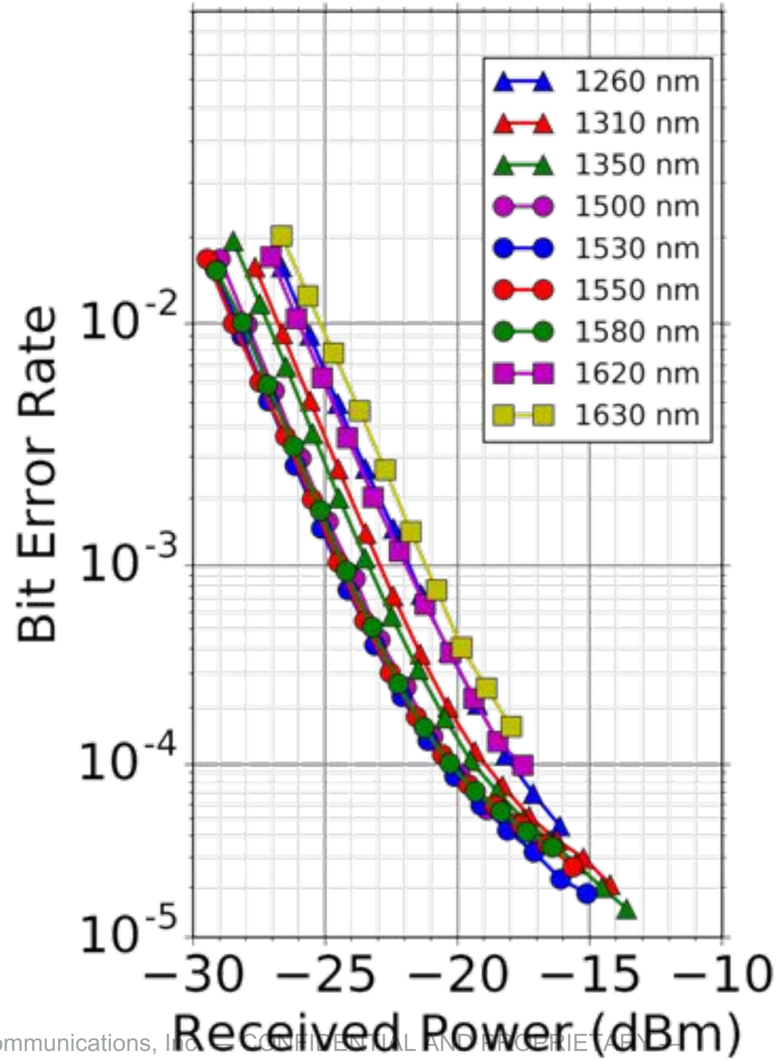
Dual-carrier MSA:
variable data rate of 2x100G, 2x150G, 2x200G

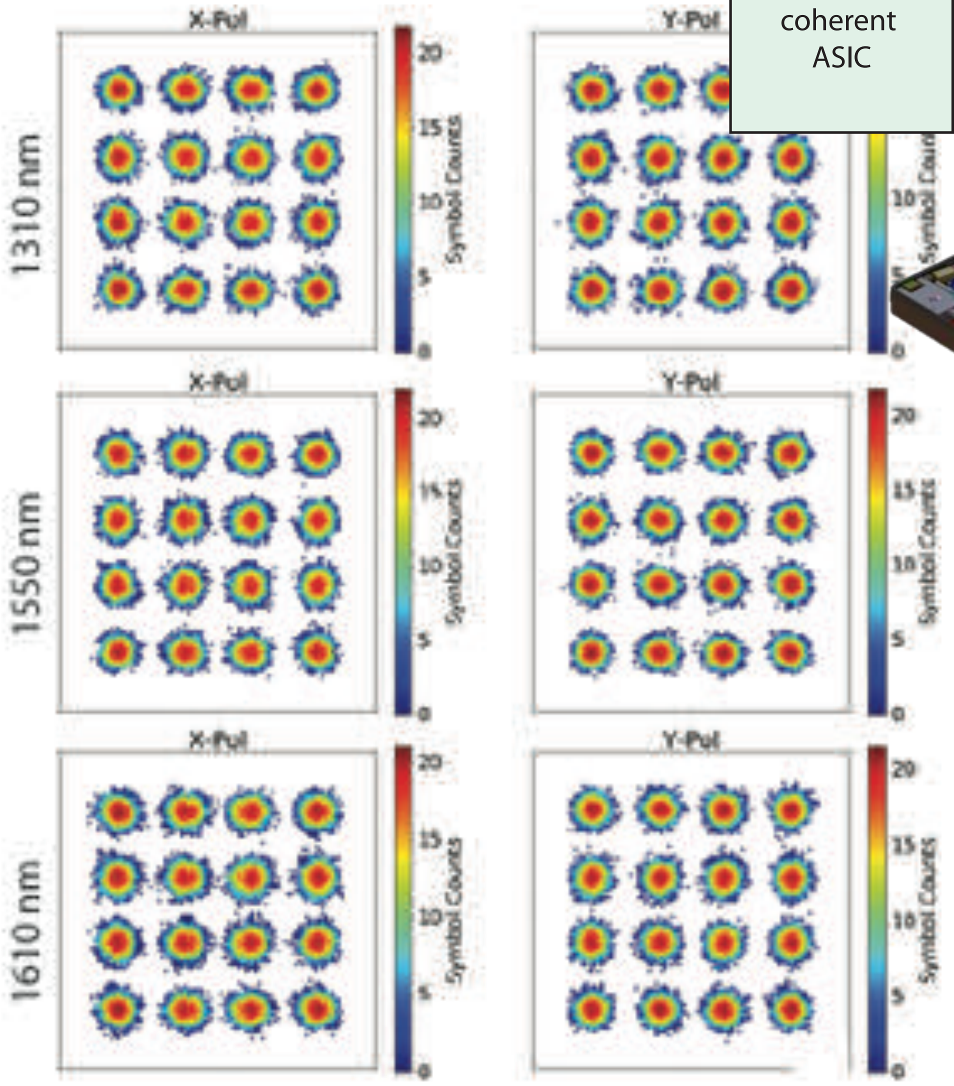


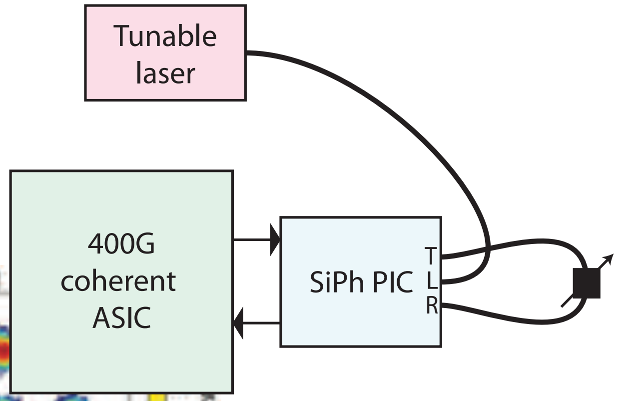
Results of two lanes are super-imposed.

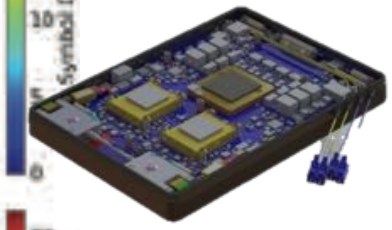
370-nm bandwidth demonstration

240 Gb/s 16-QAM

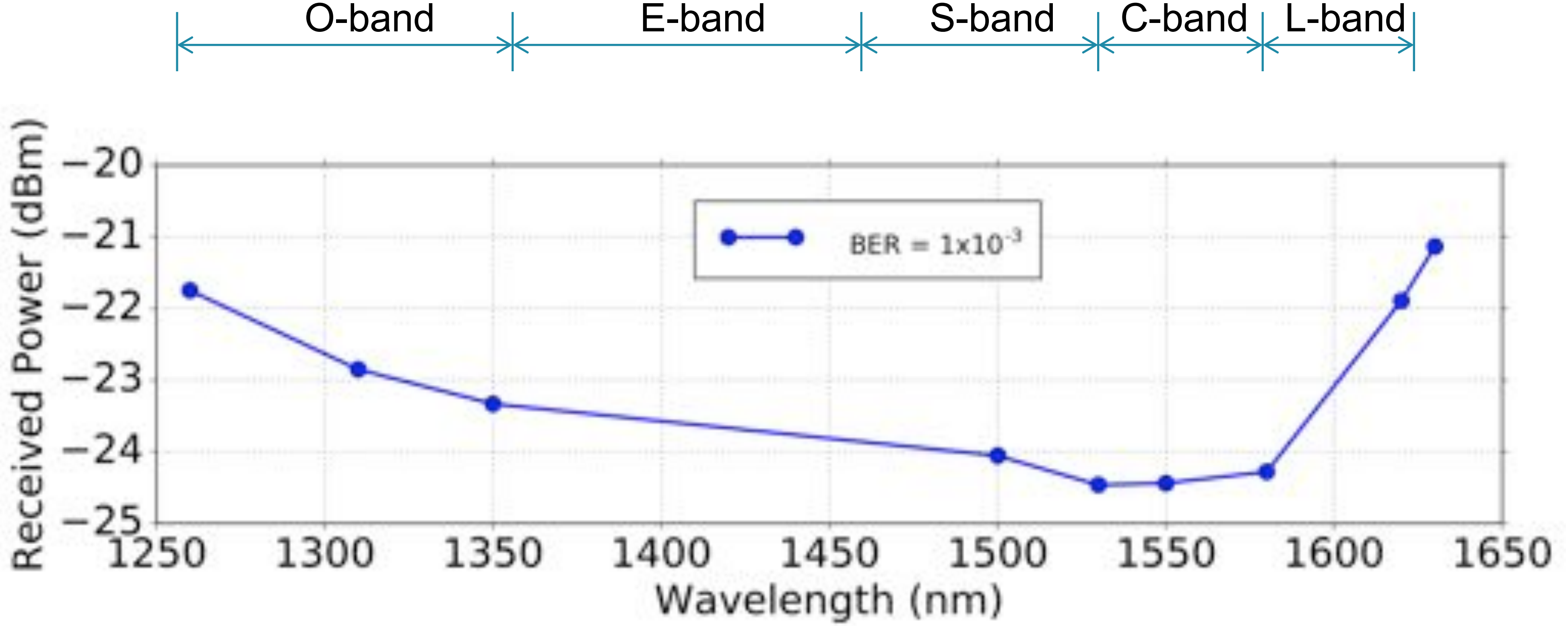








Received power at 10^{-3} BER



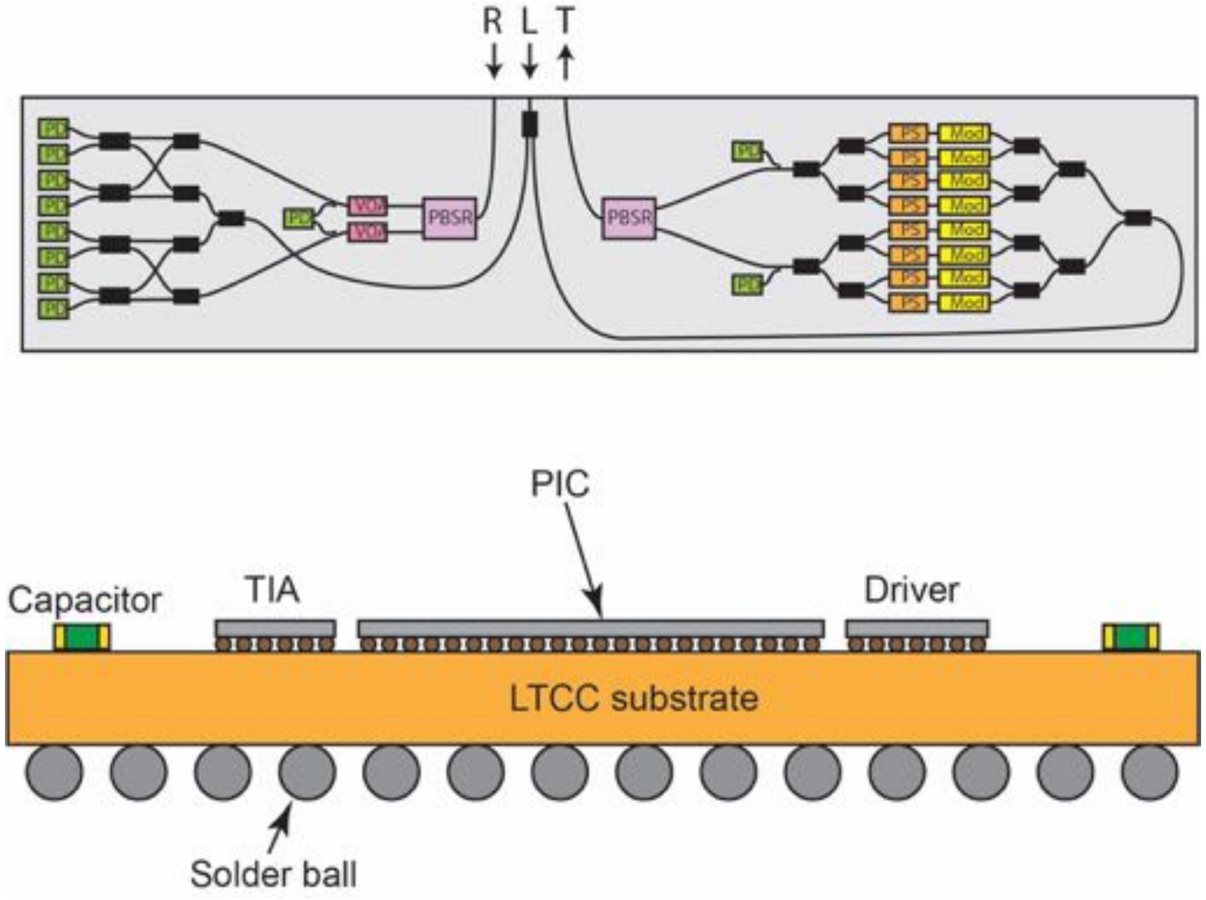
240 Gb/s, 16-QAM

Tx loss variation = 3.7 dB

Rx loss variation = 3.5 dB

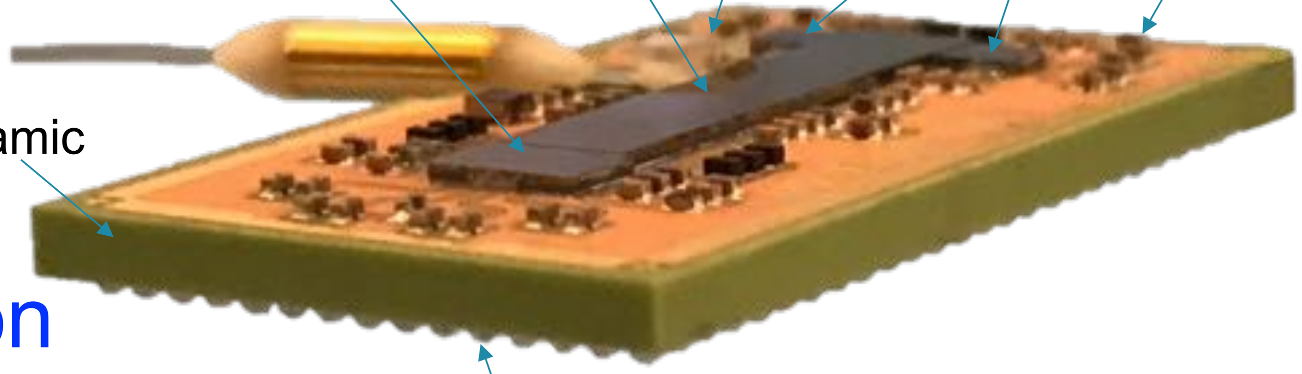
Reduced cost packaging

BGA schematic



Advantages of PIC BGA

- Lower cost
- Higher speed
- Smaller footprint
- Improved heat dissipation
- Leads to ASIC + PIC co-packaging



21.6mm x 13.0mm
369 balls, 0.8-mm pitch
3.5mm height with lid

Lower cost

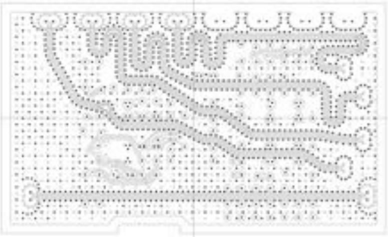
- Package
  - Single-step manufacturing process
  - Fewer parts
  - Basically a small PCB
- Assembly of package
  - Automated passives placement
  - Automated die bonding
- Assembly into module
  - Treated as regular SMT component

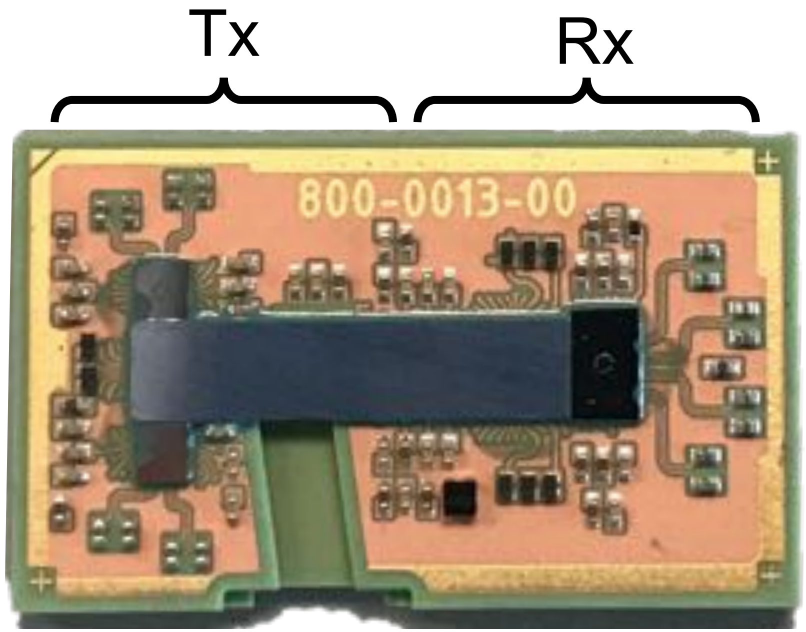
Higher speed

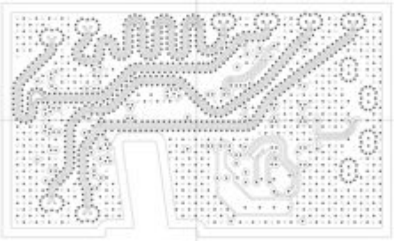
- No wire bonds
- Copper, rather than tungsten, traces

Smaller footprint

- No package pins
- Smaller footprint for both package and PCB traces



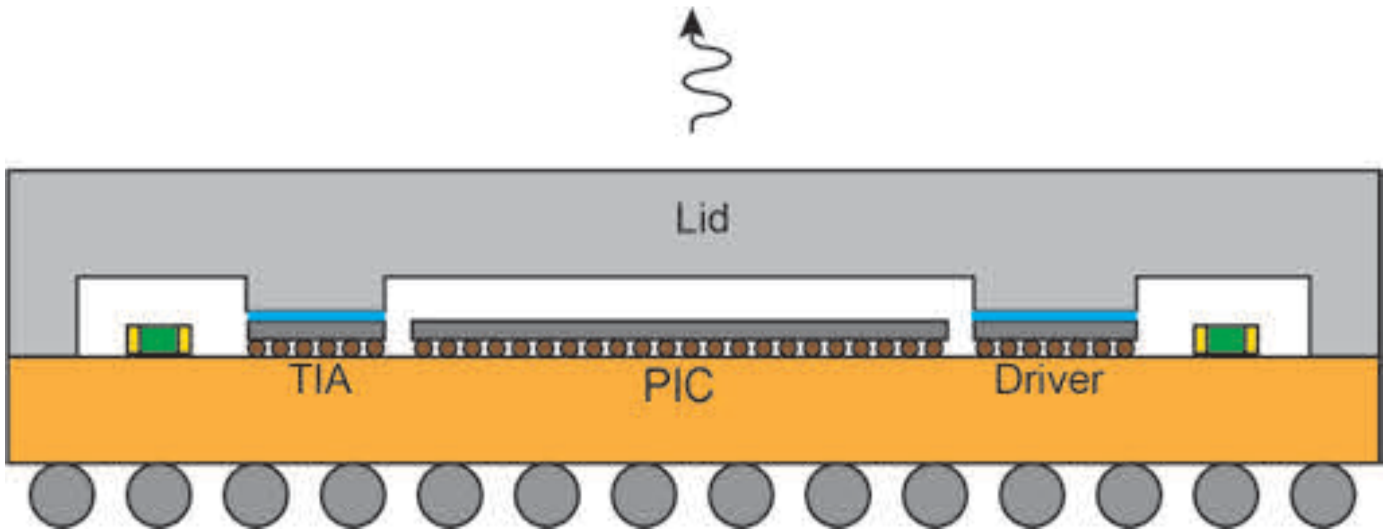




Routing to match ASIC is done inside substrate, so PCB traces can be very short

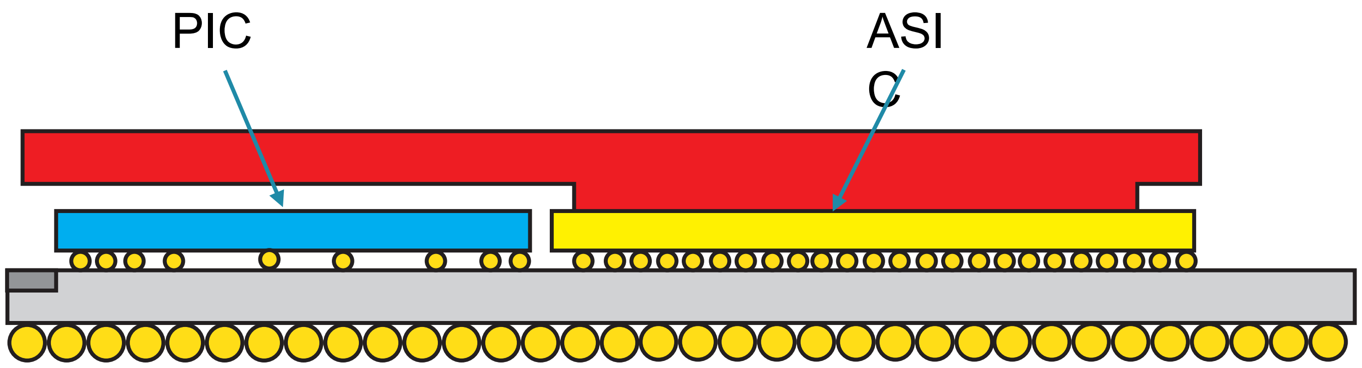
Improved heat dissipation

- Heat flows directly from die backside to lid

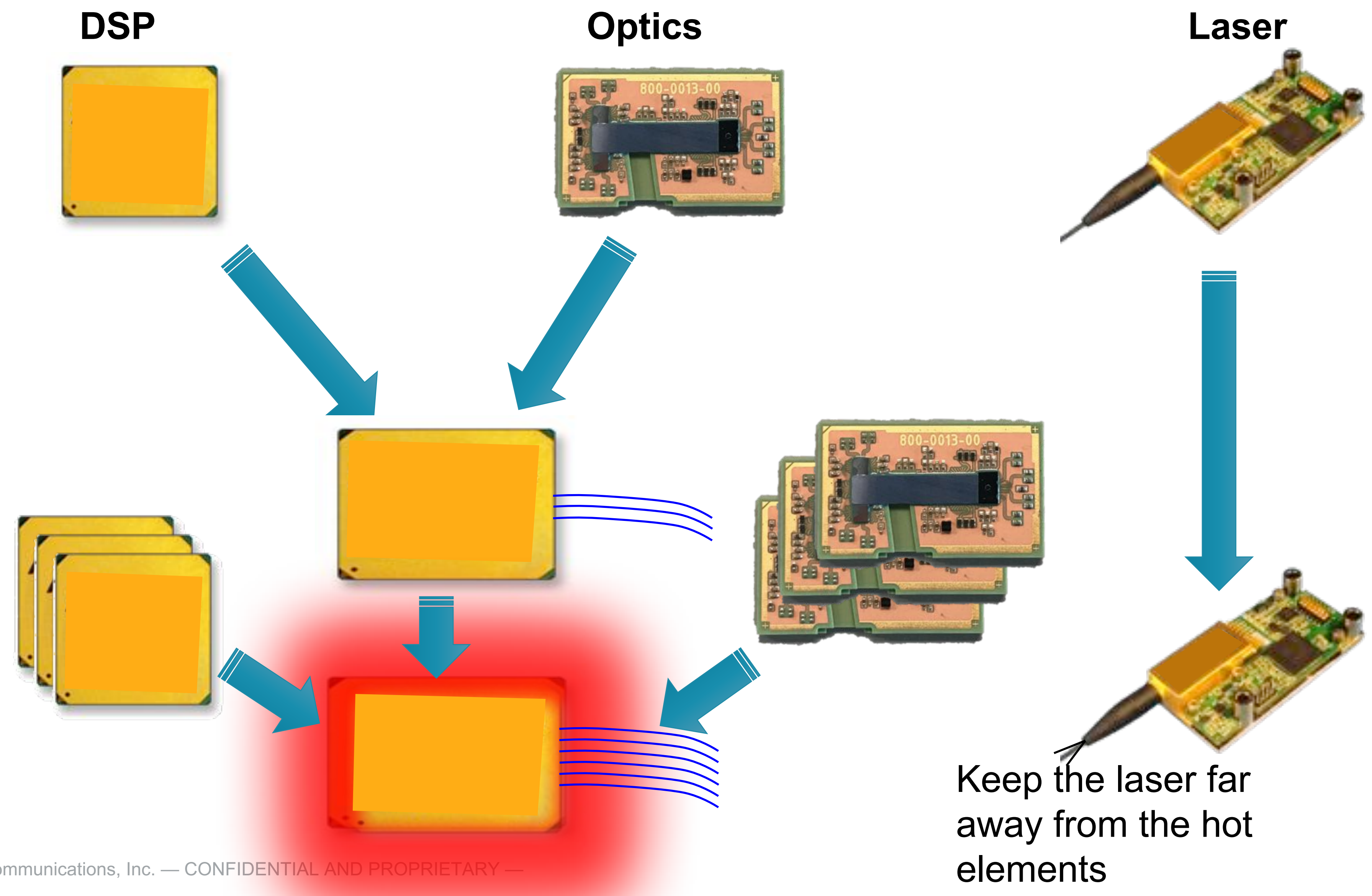


ASIC+PIC co-packaging

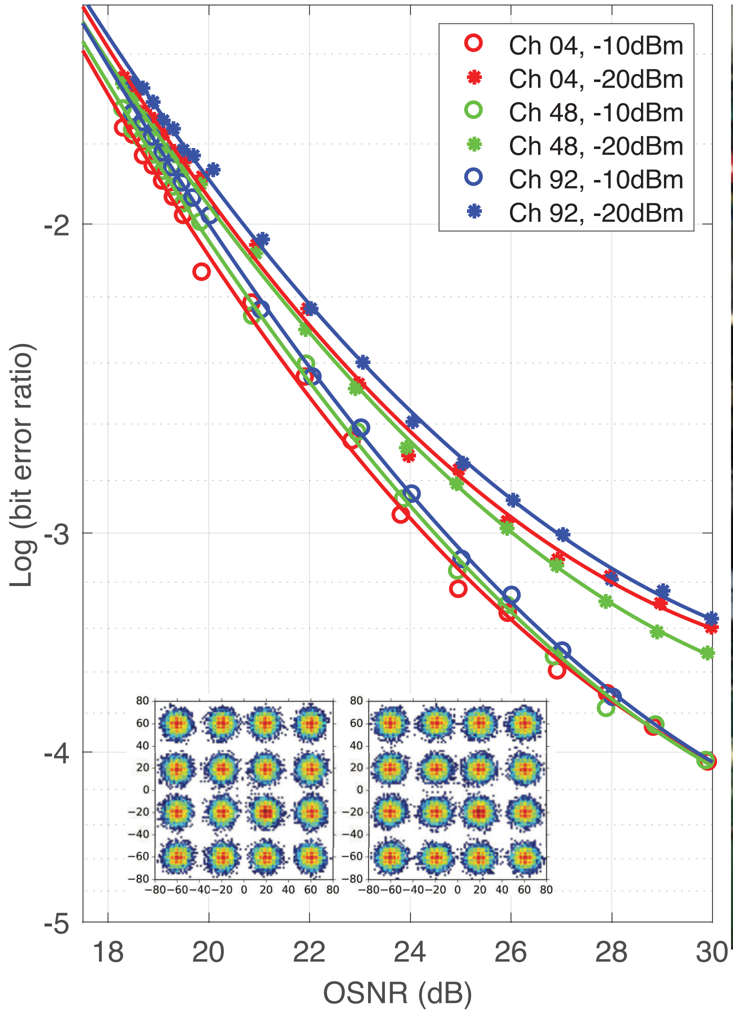
- Very high bandwidth connections
  - High speed analog signals never leave the package
- Smaller footprint
- Lower cost

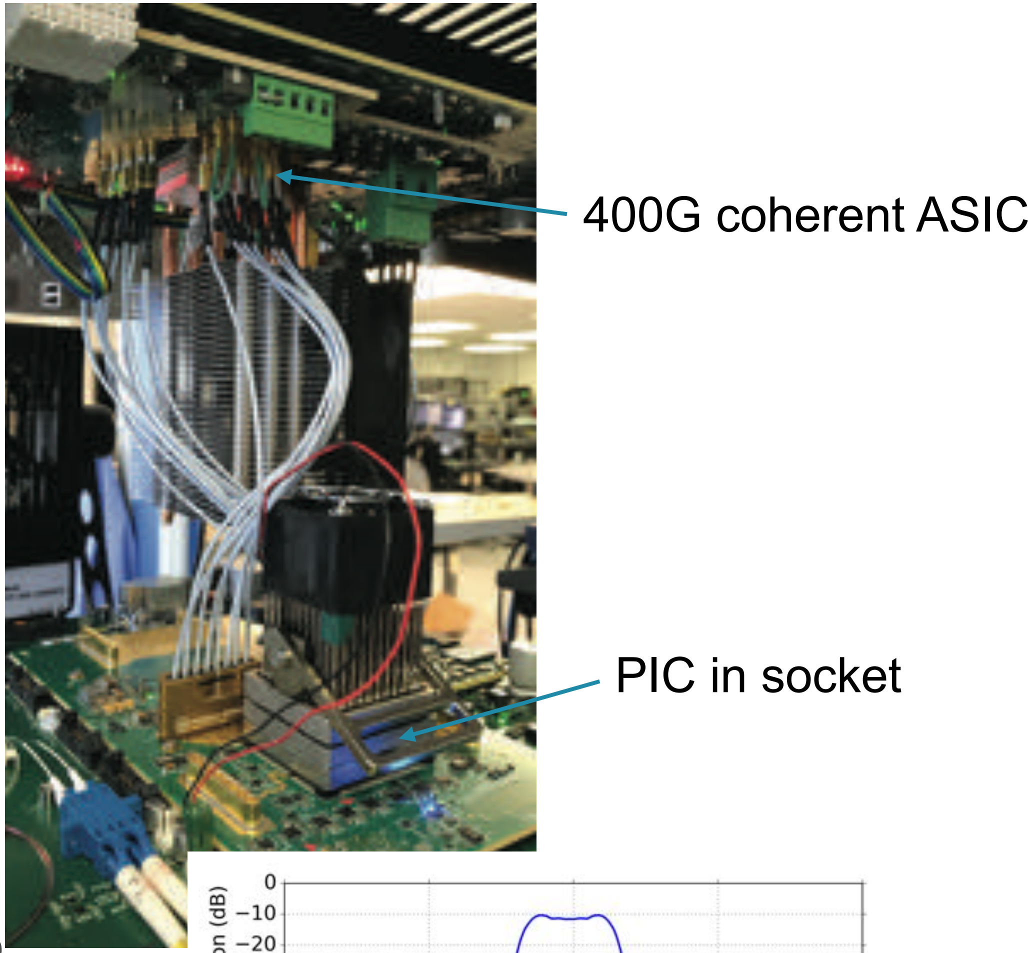


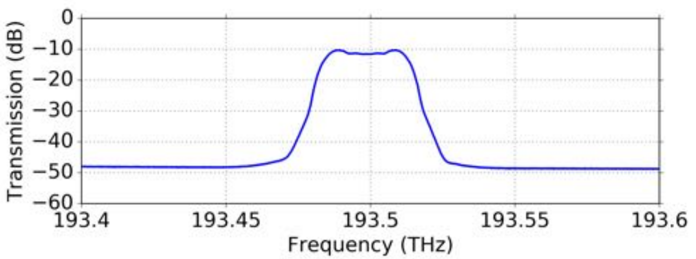
Future evolution of coherent transceivers



240-Gb/s BGA testing



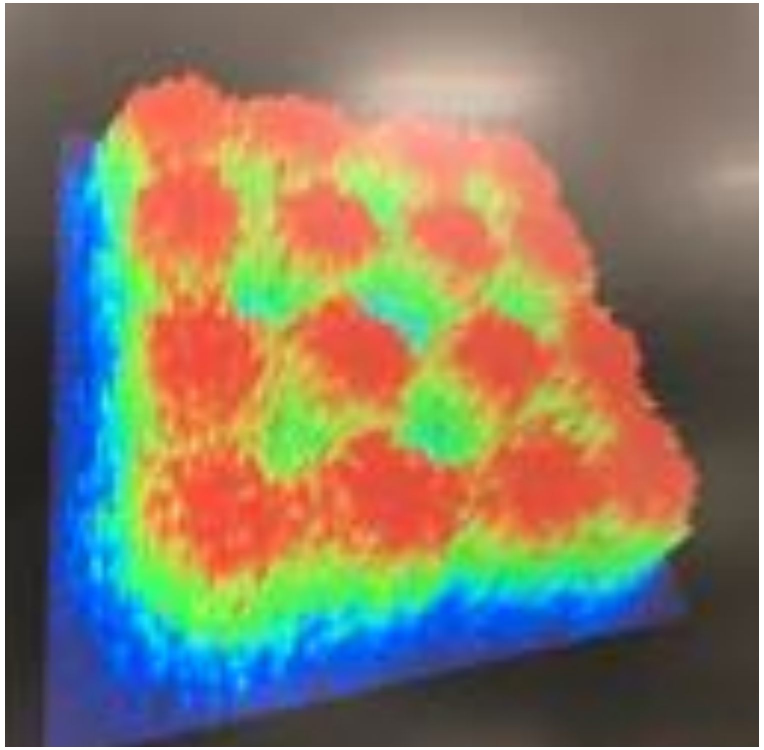




64-Gbaud testing

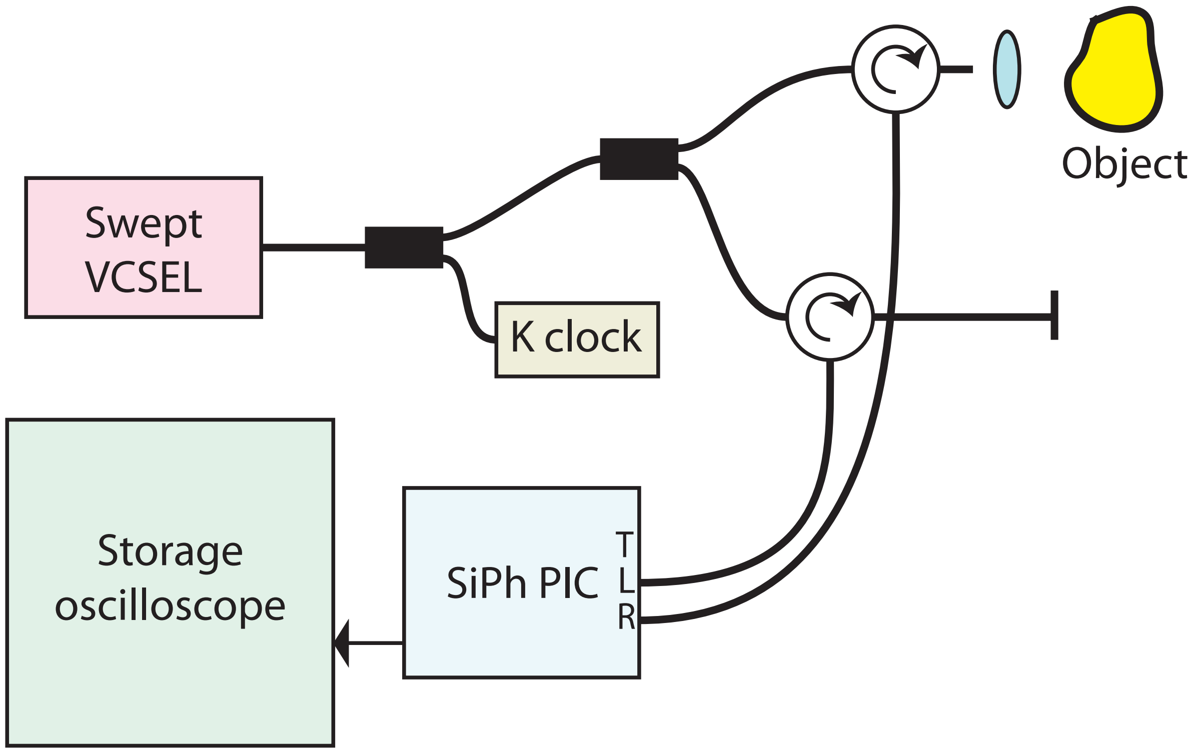
BGA PIC SMT on PCB

16 QAM, single-pol 200-Gb/s



Imaging applications using SiPh coherent technology

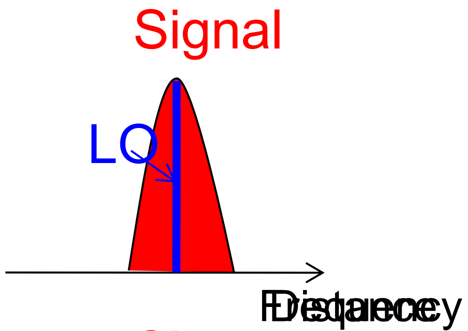
Optical coherence tomography



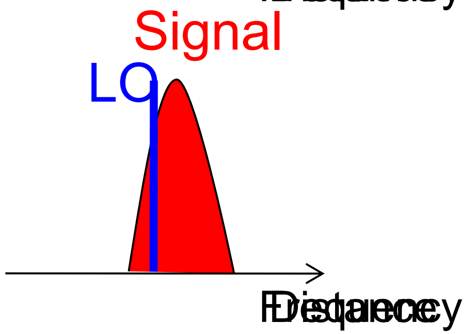
In collaboration with MIT and ThorLabs

Types of coherent detection

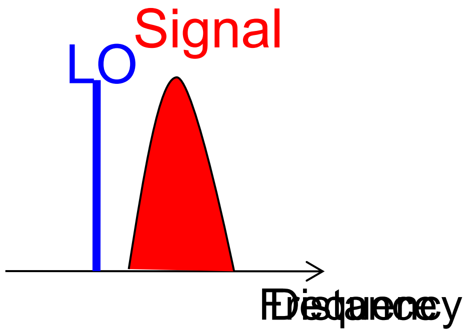
Homodyne



Intradyne



Heterodyne



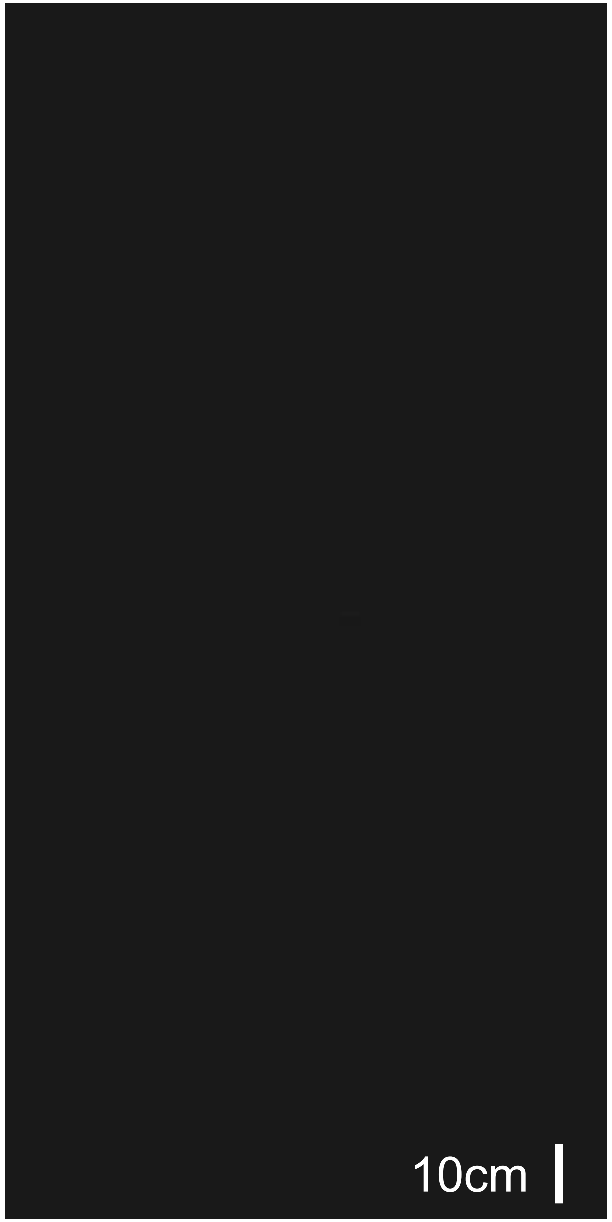
OCT imaging of 1 m^3

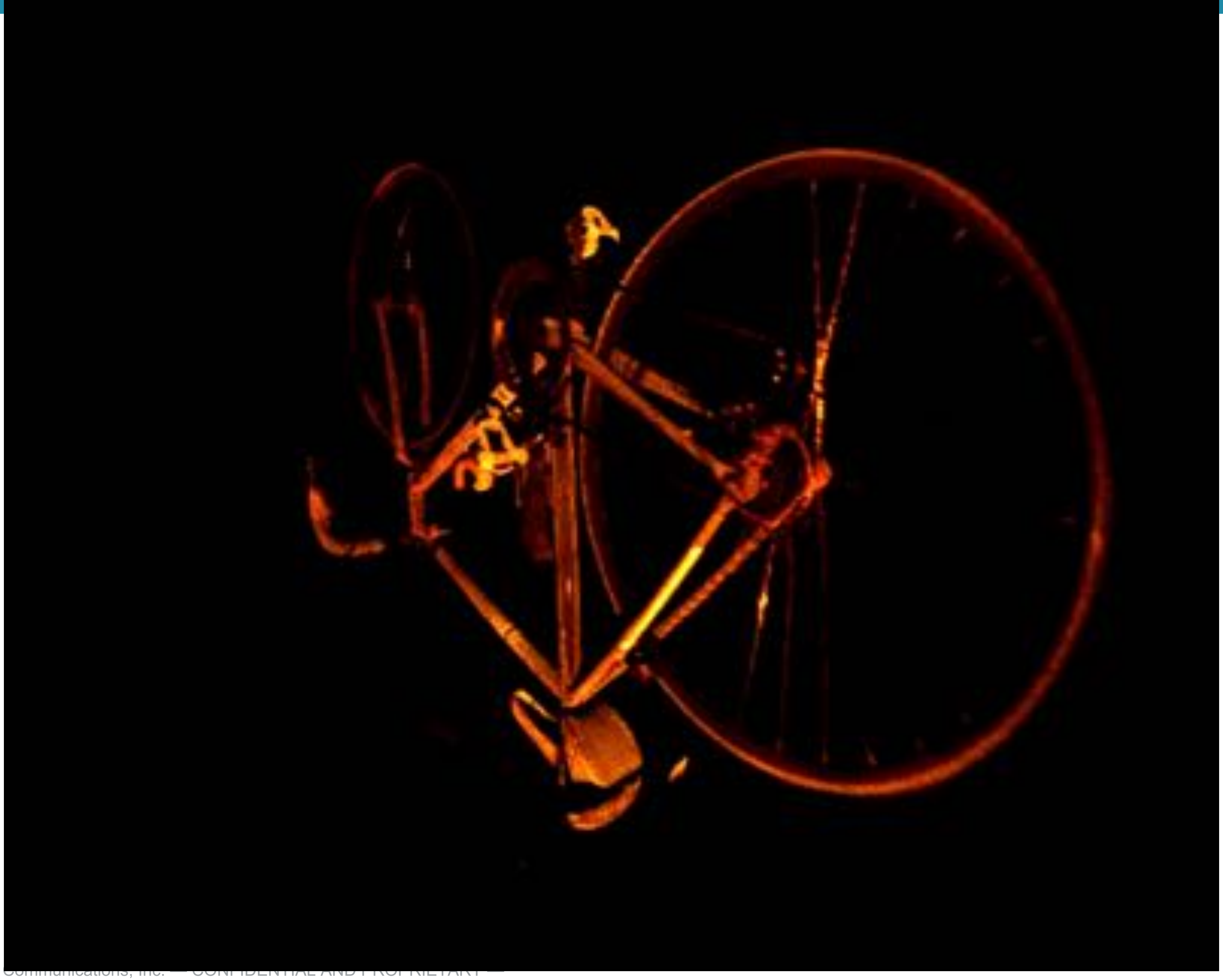
D
C

- Scan pattern: 1000x1000 A-scans/volume
- Scan volume (~200cm depth, ~100cm horizontal, ~100cm vertical)
- Edge of chess board to back of mannequin ~80cm
- 0.4TB/volume, 200,000 points/A-line

ACACIA COMMUNICATIONS, INC.

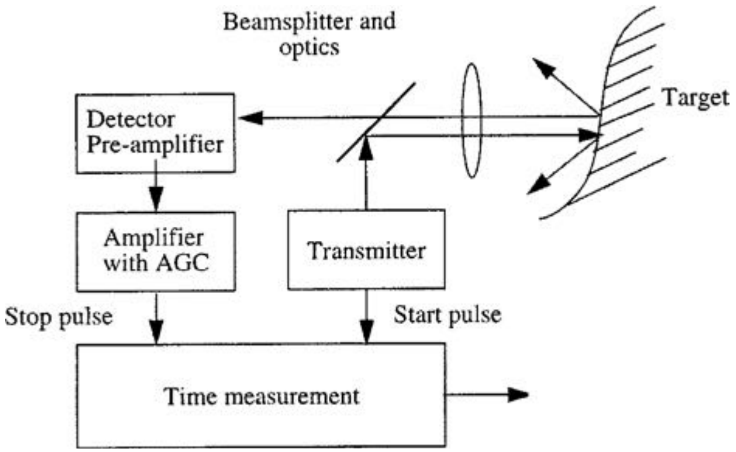
Meter range OCT for 3D documentation


10cm

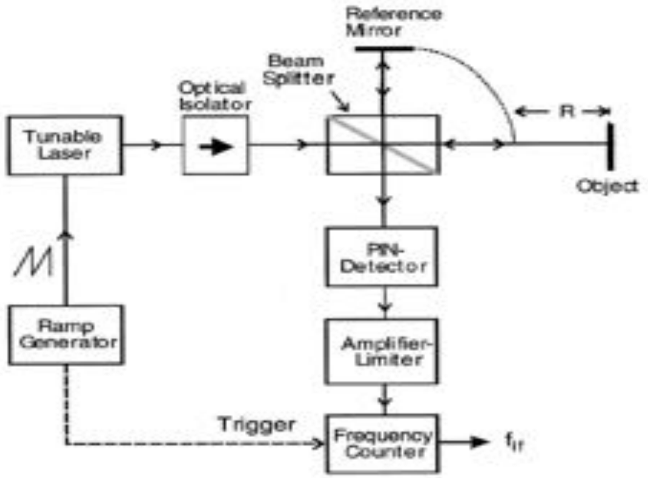


LiDAR

- Pulsed time-of-flight (TOF)
  - Simple
  - All today's LiDAR products employ TOF
  - Requires APDs
  - Most use 905 nm (1550nm is eye safe)



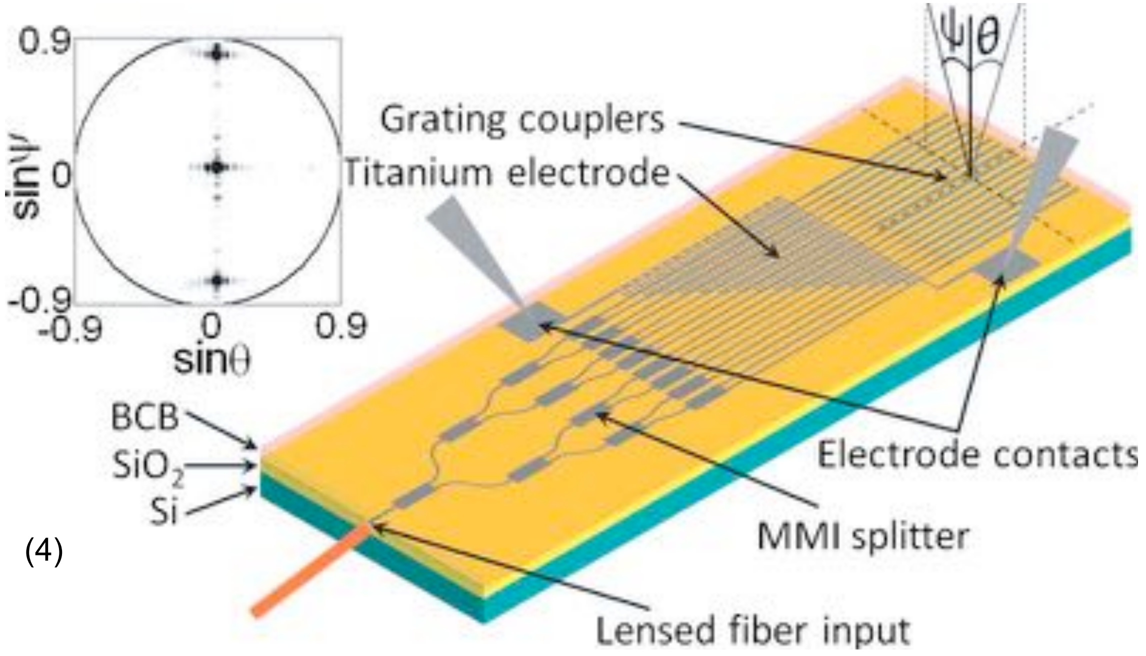
- Frequency modulated continuous wave (FMCW) (i.e., **coherent**)
  - More sensitive
  - Can use regular photodiodes
  - Gives more information (phase, Doppler shift)



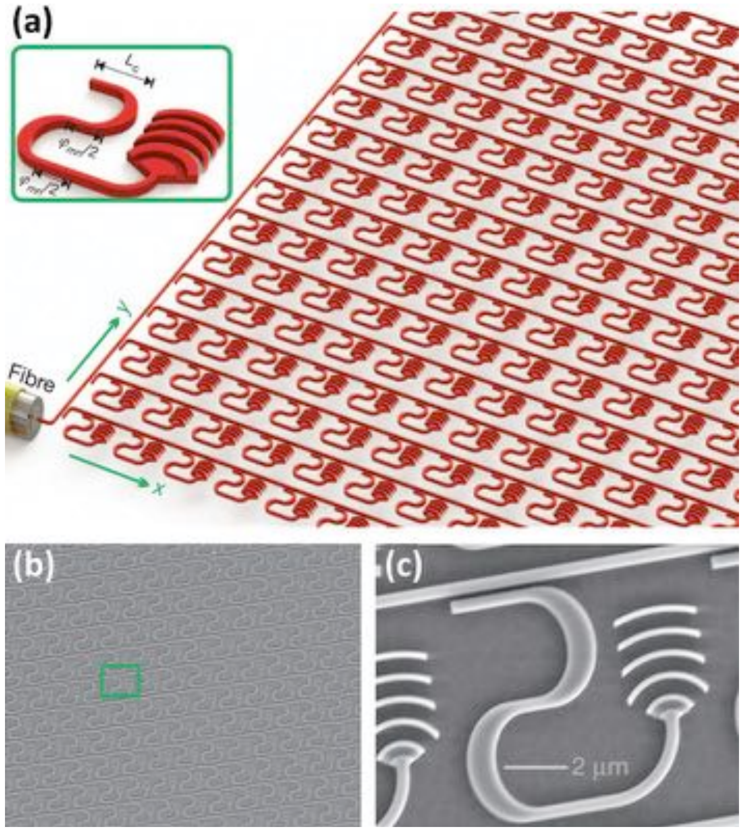
Ref: Amann, Markus-Christian "Laser ranging: a crtl review of usual techniques for distance measurement." Optical Eng 40.1 (2001): 10-19.

Phased-array beam steering using silicon photonics

(4)



K Van Acoleyen, et al., Opt. Lett, 2009.



J. Sun, et al., Adv. Photon. for Comm., 2014.

Conclusion

Conclusion

- SiPh allows for very high complexity with high yield and low-cost packaging
- Coherent optics is a killer application for SiPh

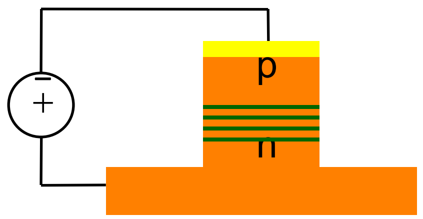
Thank you

Acknowledgments: B. Mikkelsen, E. Swanson, M. Givhechi, C. Rasmussen, L. Chen, R. Aroca, S. Azemati, J. Heanue, G. Ali, G. McBrien, Li Chen, B. Guan, H. Zhang, X. Zhang, T. Nielsen, H. Mezghani, M. Mihnev, N. Sauer, C. Yung, M. Xu, J. Fujimoto, B.

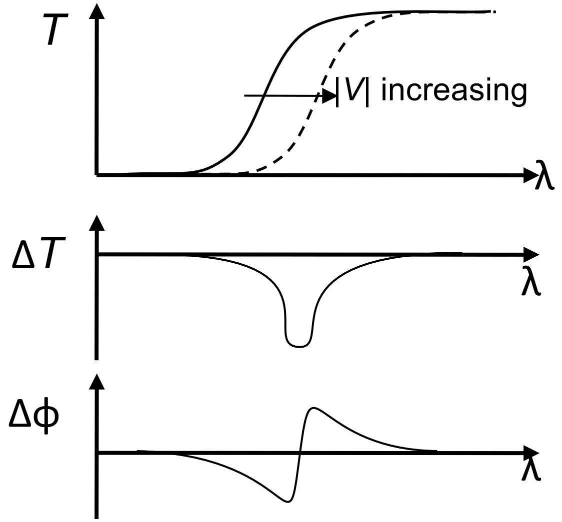
Back-up

InP & SiPh modulator comparison

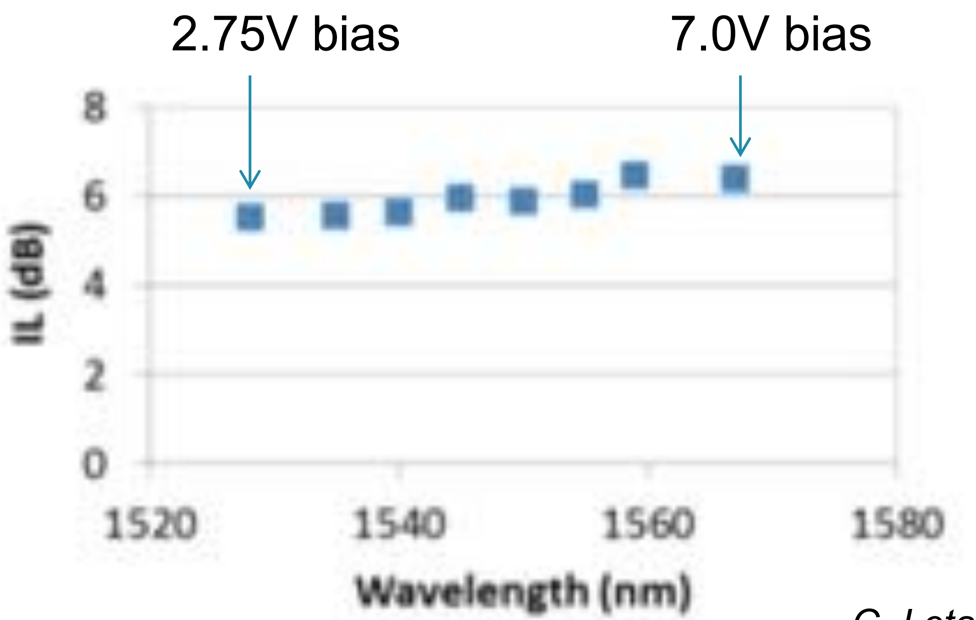
InP



π = 1 V-cm



InP IQ modulator

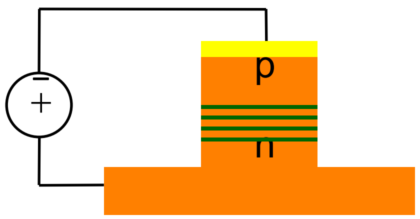


InP modulator bandwidth limited to ~40 nm

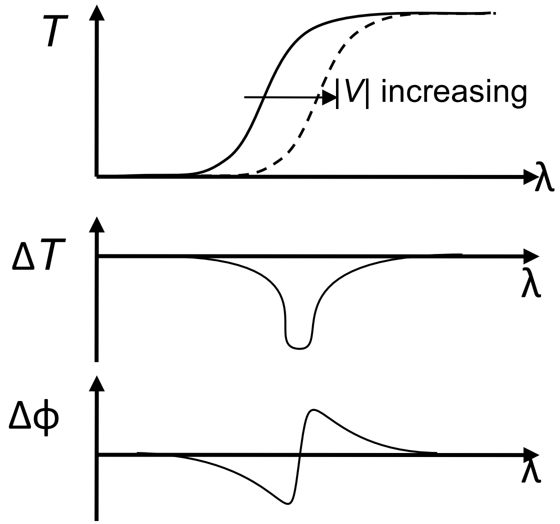
G. Letal, et al., OFC, Th4E.3, 2015.

InP & SiPh modulator comparison

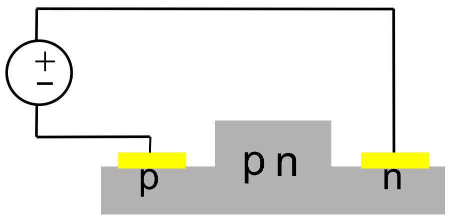
InP



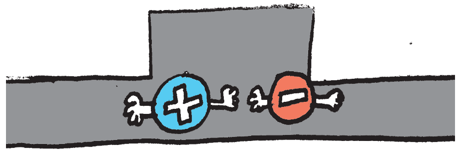
π = 1 V-cm



Si



π = 2 V-cm



$$\Delta n_r = -8.8\times10^{-22} N_e - 8.5\times10^{-18} N_h^{0.8}$$

$$\Delta n_i = 1.0\times10^{-22} N_e + 7.4\times10^{-23} N_h$$

N_e = free electron density
N_h = free hole density