Silicon photonics with 4 dB/m loss and 40 GHz photodetectors

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14/04/2021 VTT – beyond the obvious

OPTICS

Optical/Photonic Interconnects for Computing Systems
14-15 April 2021

Outline

- Introduction to 3 µm SOI PICs
- Waveguides with 4 dB/m loss
- 40 GHz Ge photodiodes
- VCSEL integration on 3 µm SOI for 2 Tb/s transceivers
- Conclusions & outlook
- Acknowledgments

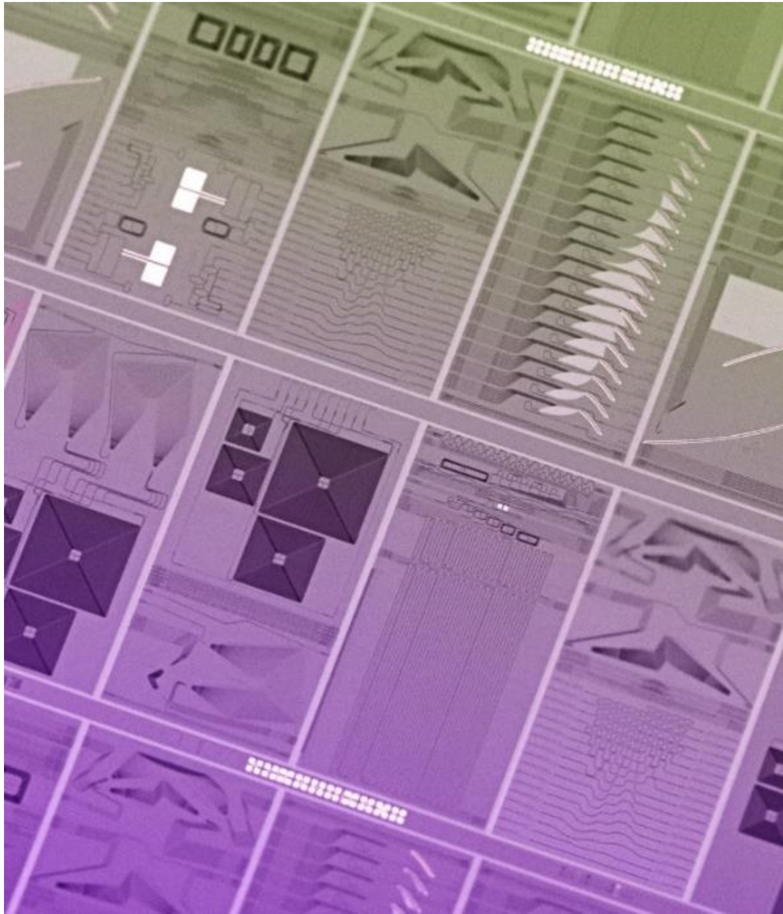
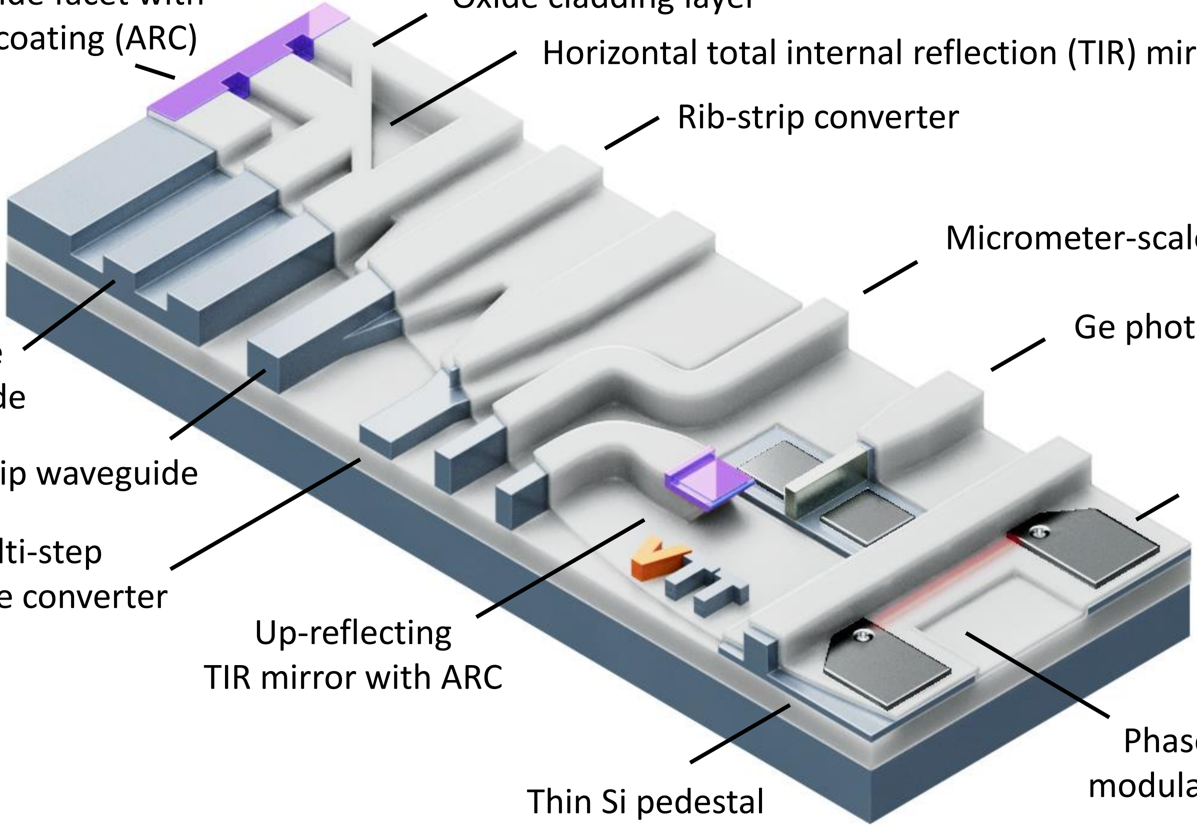


Illustration of the 3 µm SOI platform



Micron-size SOI waveguides have ultra-wide wavelength range for both TE & TM

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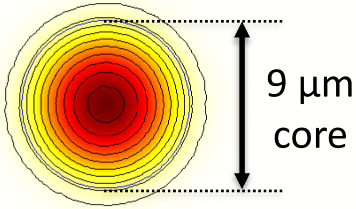
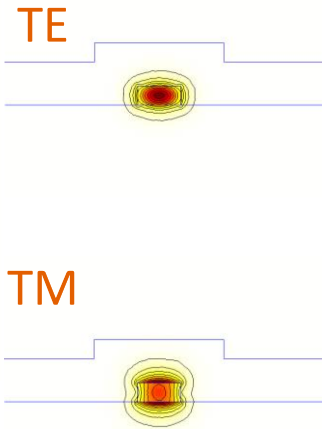
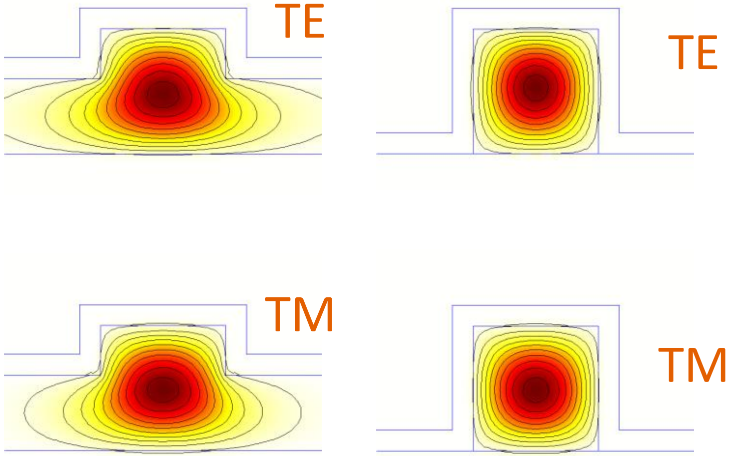


Standard single-mode fiber

Norm of the E field plotted as a function of wavelength (material absorption and dispersion ignored)



220 nm SOI (SM strip)

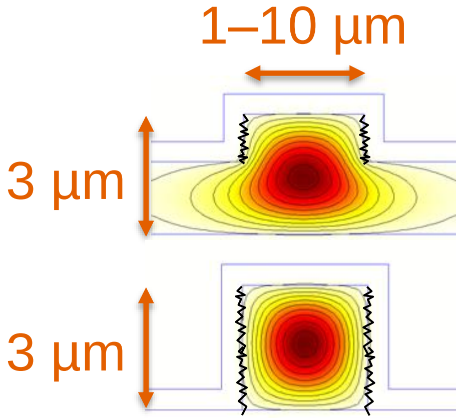


3 µm SOI (SM rib)

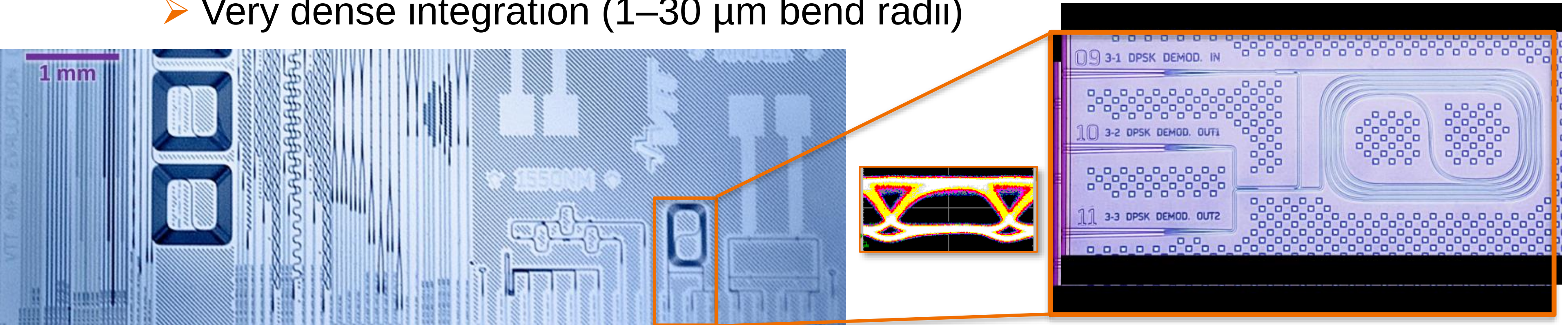
3 µm SOI (MM strip)

Fundamental benefits of micron-scale SOI waveguides

- Ultra-broadband single-mode operation of rib waveguides (from 1.2 to >4 µm wavelength)
- Ultra-high mode confinement:
  - Low propagation loss (down to 4 dB/m)
  - Dual-polarization & zero-birefringence operation
  - Reduced sensitivity to fabrication tolerances
  - Very dense integration (1–30 µm bend radii)



$n_{eff,TE} \approx n_{eff,TM} \approx n_{Si}$



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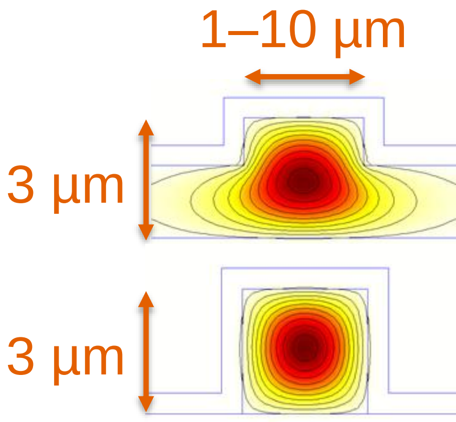
  - Dual-polarization & zero-birefringence operation
  - Reduced sensitivity to fabrication tolerances
  - Very dense integration (1–30 µm bend radii)
- Large mode field area of 2–30 µm^2:
  - End-fire coupling loss ~0.5 dB (lensed fiber)
  - Ability to handle large optical power (Watts)



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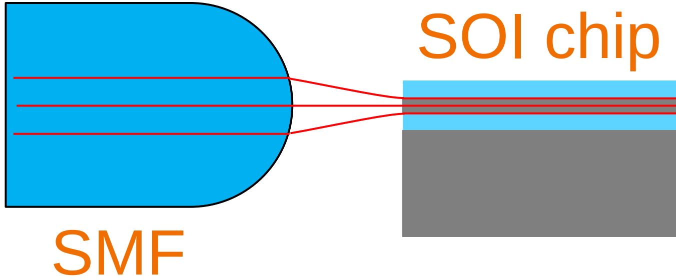
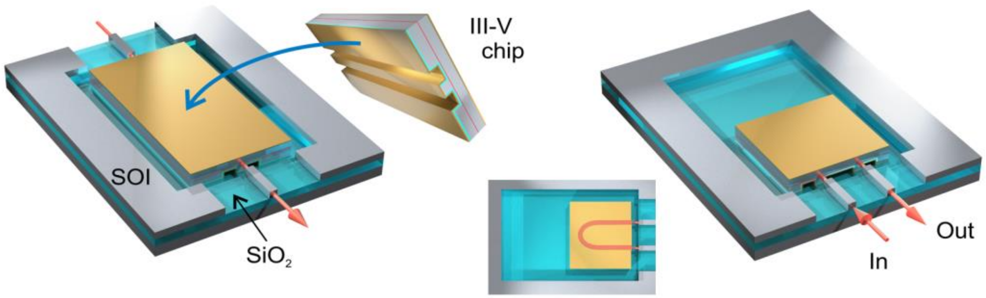


Present main limitation of micron-scale SOI waveguides

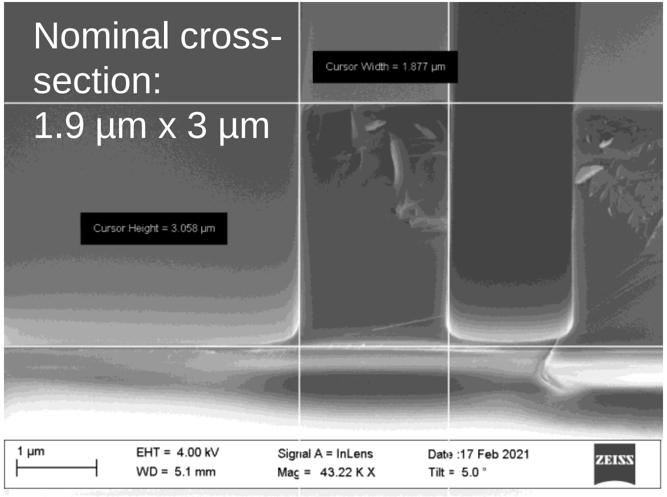
- Lack of monolithic high-speed modulators:
  - Thermo-optic modulators only reach up to ~100 kHz
  - Plasma dispersion modulators only reach up to a few GHz (due to large waveguide dimensions)
  - Plasmonic modulators could reach >>100 GHz, but they are not yet available on 3 µm SOI and they have high losses
- Alternative option:
  - Hybrid integration of directly modulated lasers or external modulators

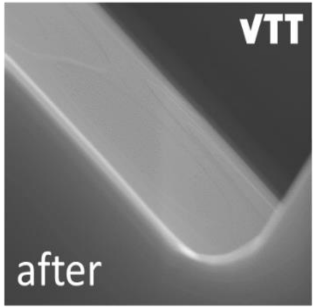


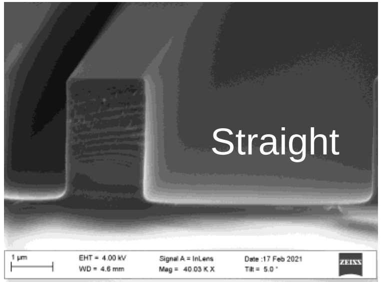
H. Tuorila et al., Appl. Phys. Lett. 113, 041104 (2018)

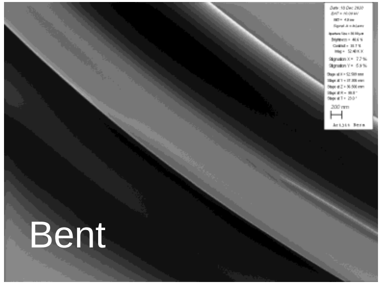
Loss reduction with hydrogen annealing

- Hydrogen annealing at 900°C significantly reduces surface roughness of the etched SOI waveguide side-walls
- Smoothening is stopped before the overall waveguide shape gets distorted and unwanted crystalline planes become visible



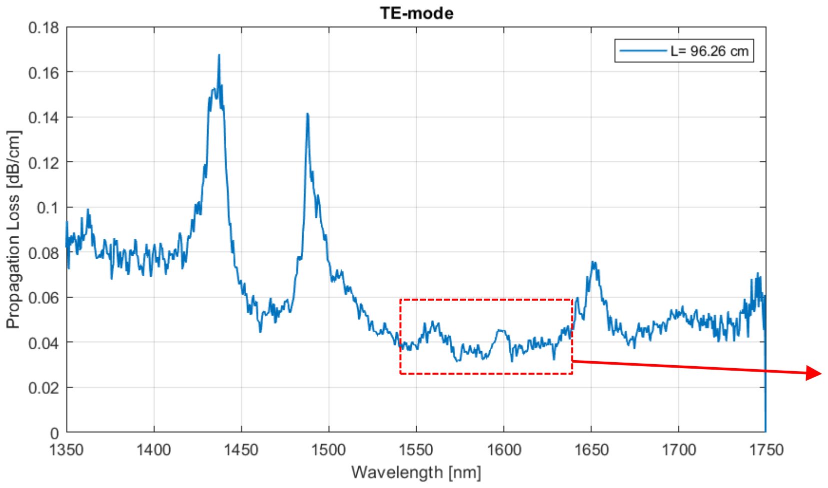


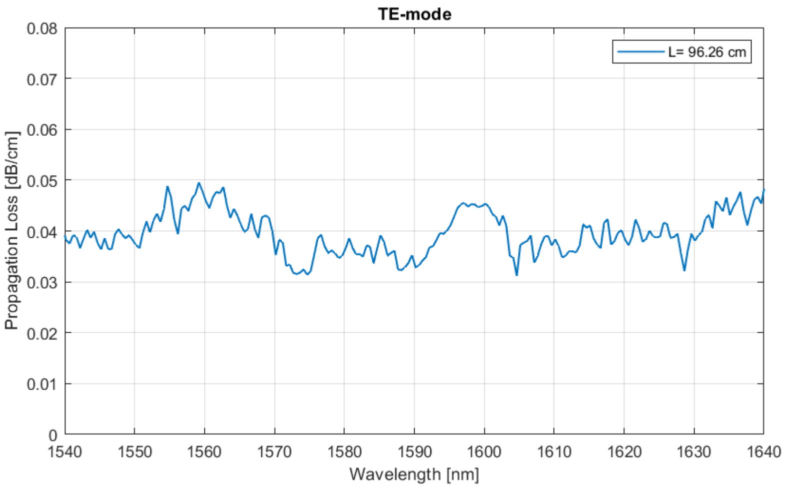




Measured propagation losses

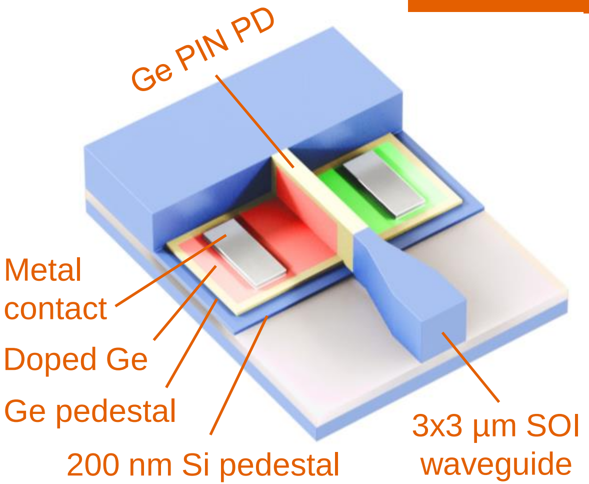
- Cut-back measurement with 96 and 146 cm long spirals and a straight waveguide
- Average loss 4 dB/m in the 1540–1640 nm wavelength range
- Spectral oscillations outside this range, possibly due to higher order mode excitation
- Loss was slightly higher for TM polarization (vs. TE)

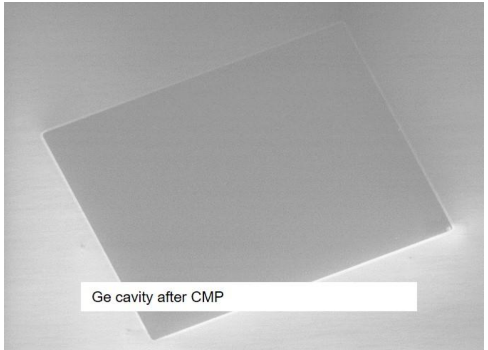


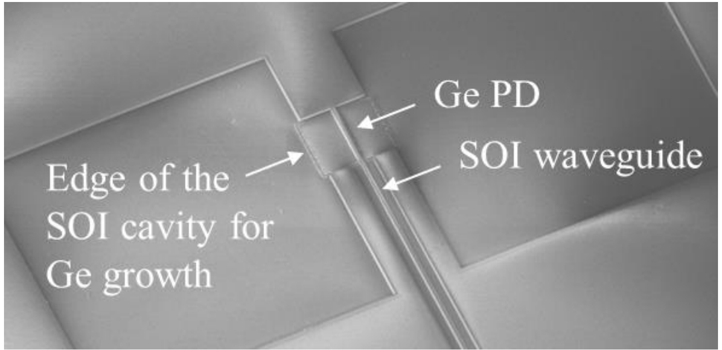


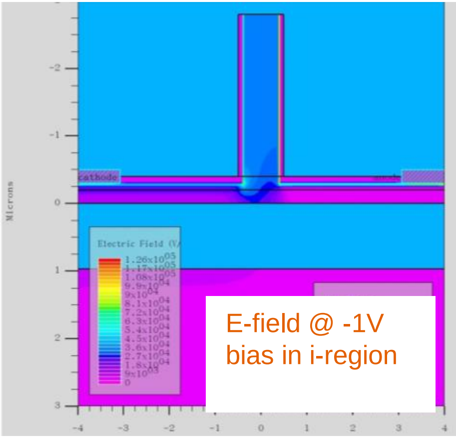
40 GHz Ge photodiode

- 1 µm wide and 9 µm long Ge PD waveguide end-fire coupled to a horizontally down-tapered Si waveguide
- Doped Ge sidewalls and 200 nm thick Ge pedestal
- Default wavelength 1550 nm
- Sidewall doping enables high and uniform E-field in the 700 nm wide i-region with low bias
  - → Short average transit time
  - → Transit-time-limited bandwidth ~**40 GHz**
- Selective Ge epitaxy on a thin SOI pedestal



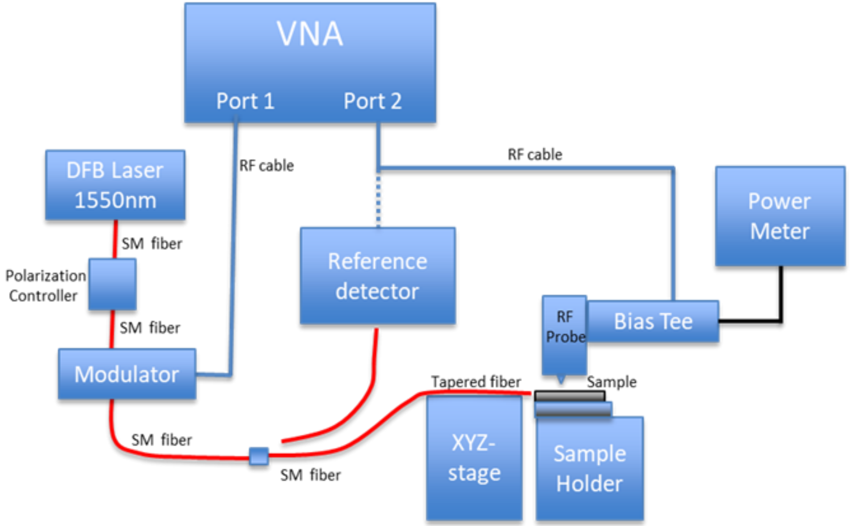


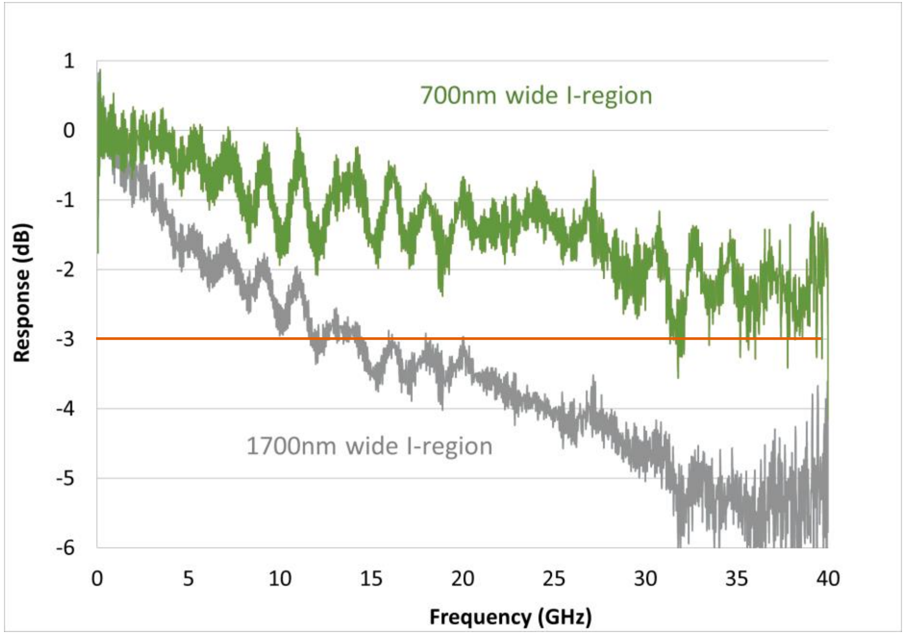




40 GHz Ge photodiode

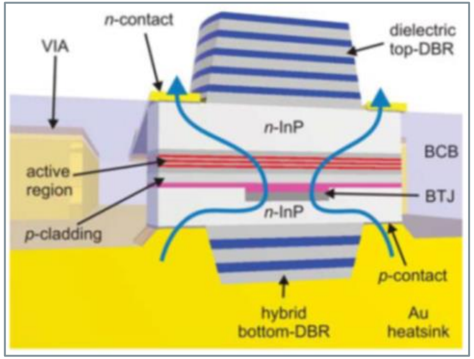
- Measured 3 dB bandwidth is ~40 GHz as simulated (transit time limited)
- Available measurement equipment didn't reach beyond 40 GHz





Hybrid 2 Tb/s transceiver

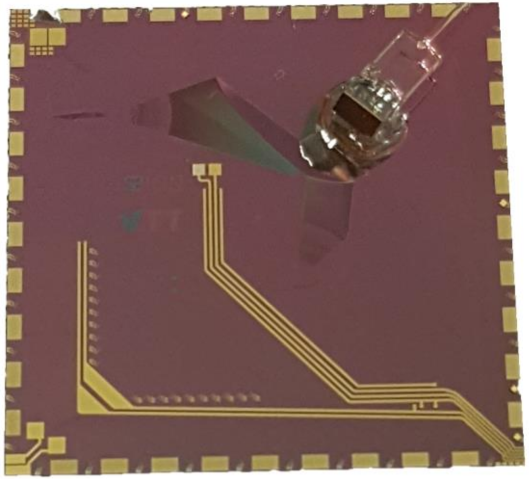
- 1550 nm VCSELs coupled to 3 µm SOI with up-reflecting TIR mirrors
- 40 VCSELs and 40x1 MUX to get 2 Tb/s output per SOI chip

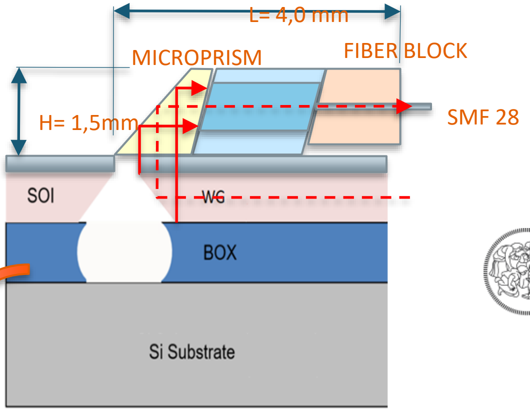


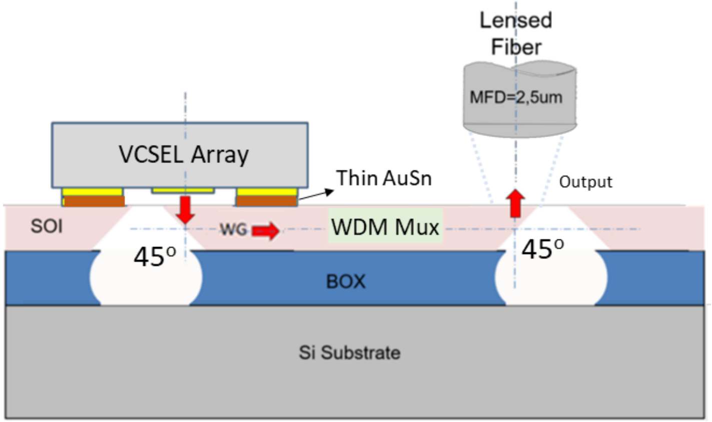
PASSION

x40

http://www.passion-project.eu







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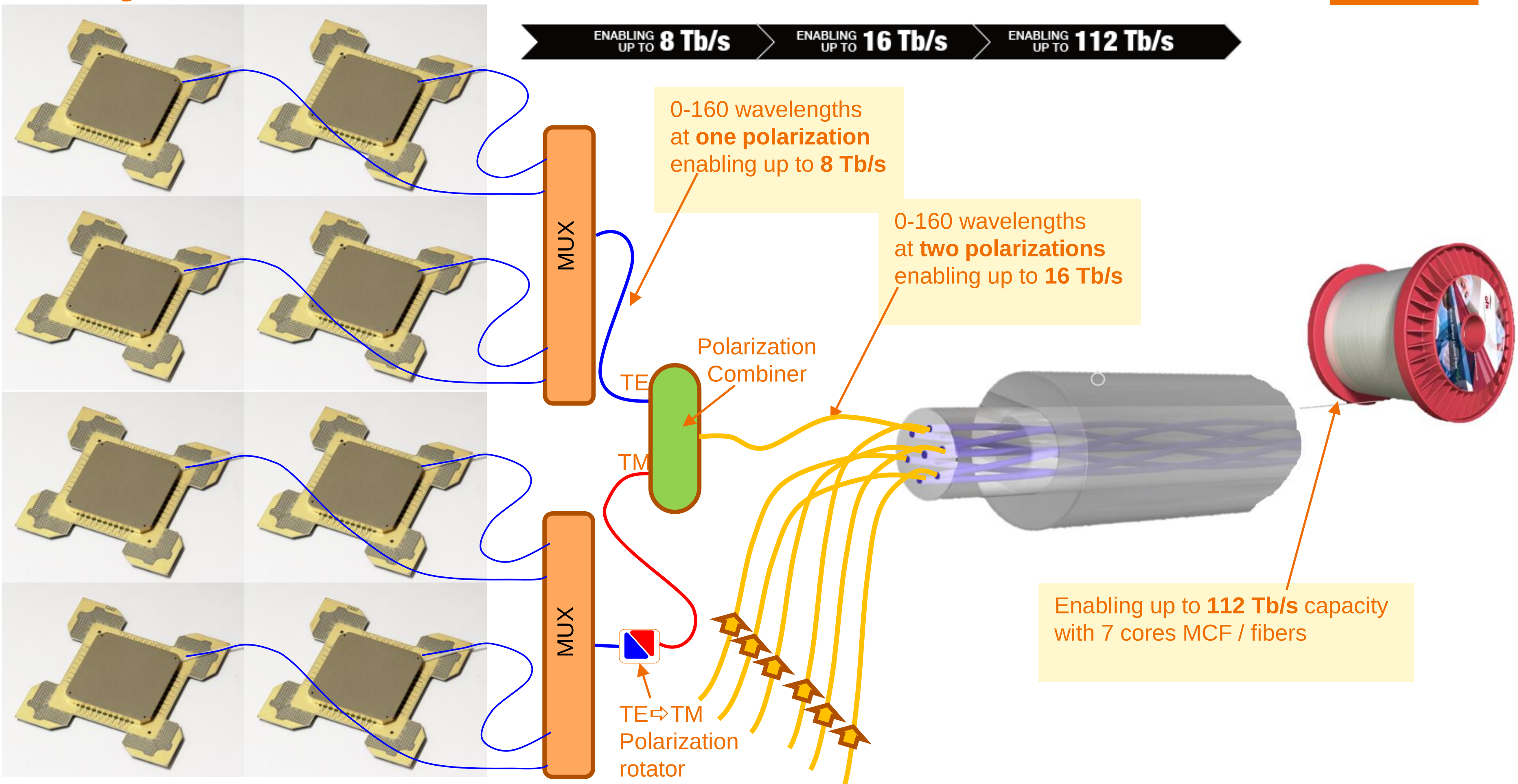
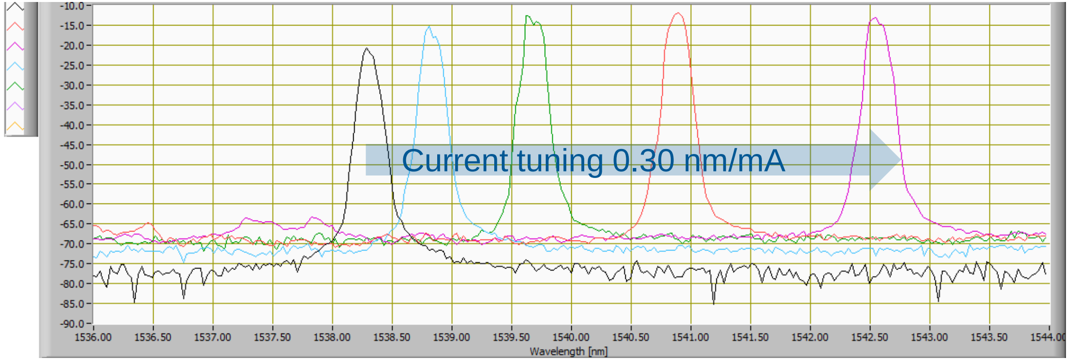
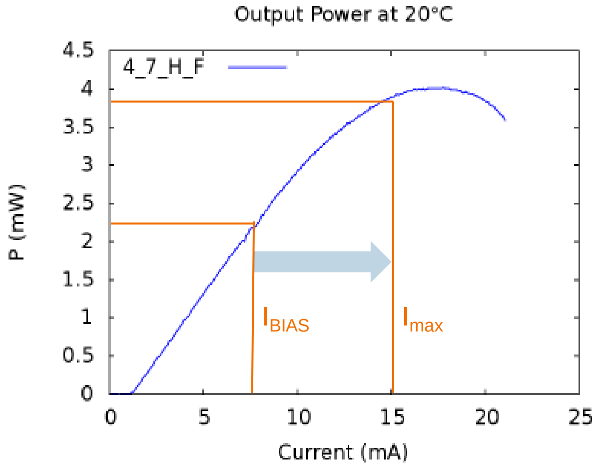
Hybrid 2 Tb/s transceiver for metro networks



VCSEL tuning and driving

- VCSEL wavelength can be tuned with current and temperature



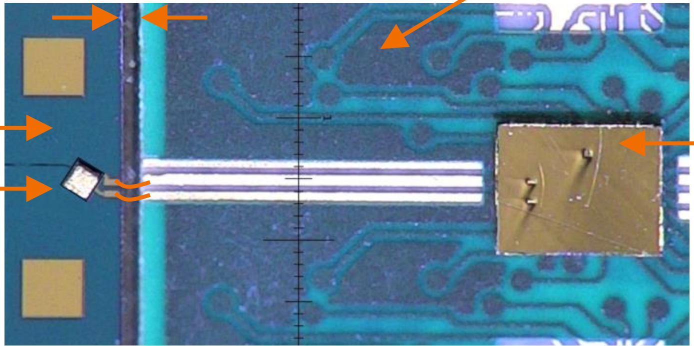


100 µm air gap for thermal decoupling

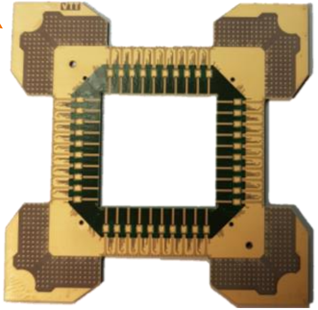
Electrical interposer

PIC

VCSEL

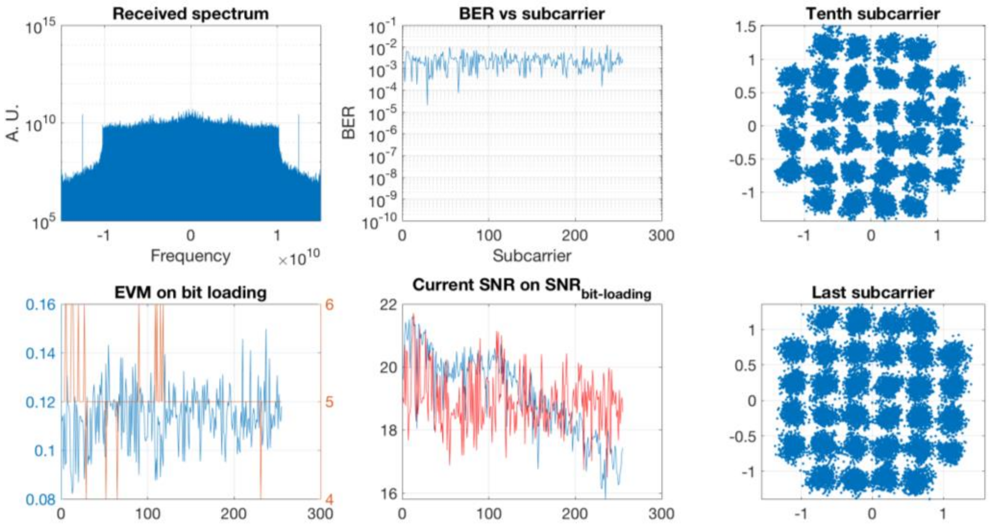


VCSEL Driver

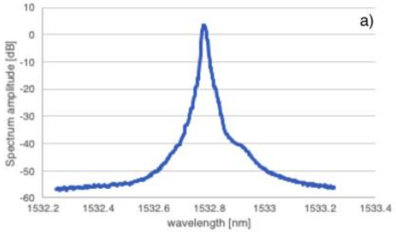


VCSEL modulation test results

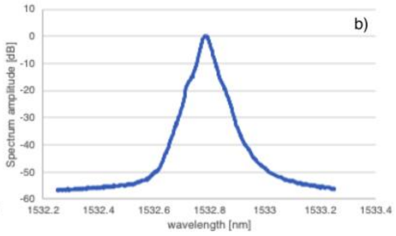
- Tx capacity with DMT modulation: 48.7 Gb/s, **50.2 Gb/s** with chip equalizer “on”



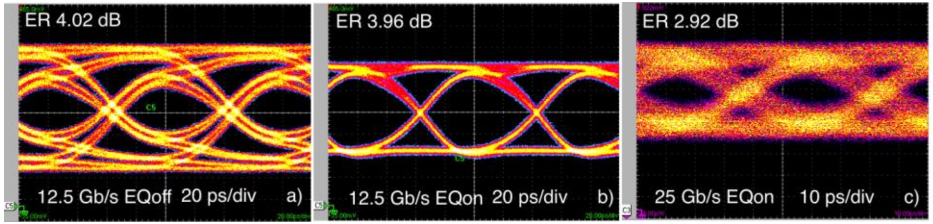
CW spectrum



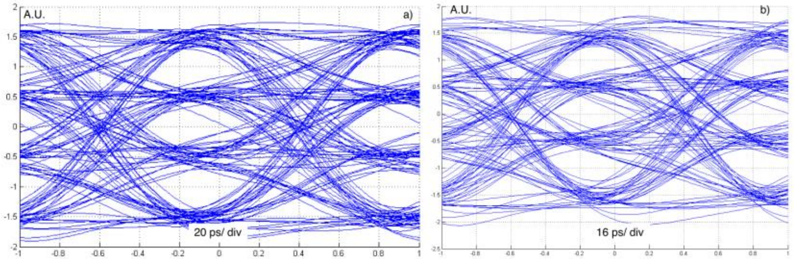
Modulated spectrum



OOK modulation up to 25 Gb/s

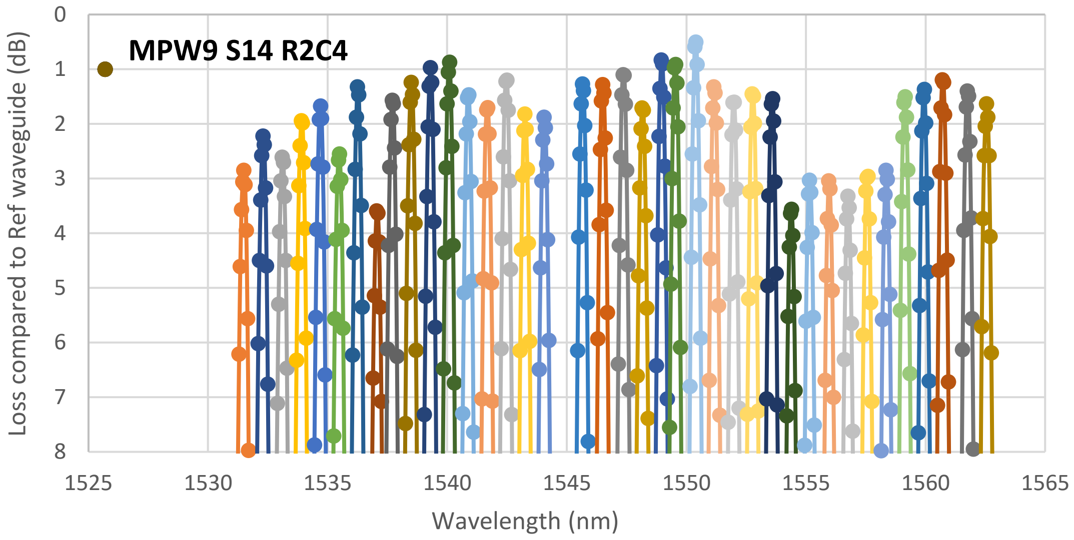


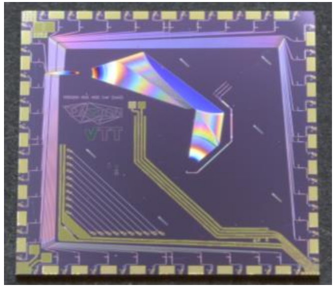
4-PAM modulation up to 12.5 Gbaud/s



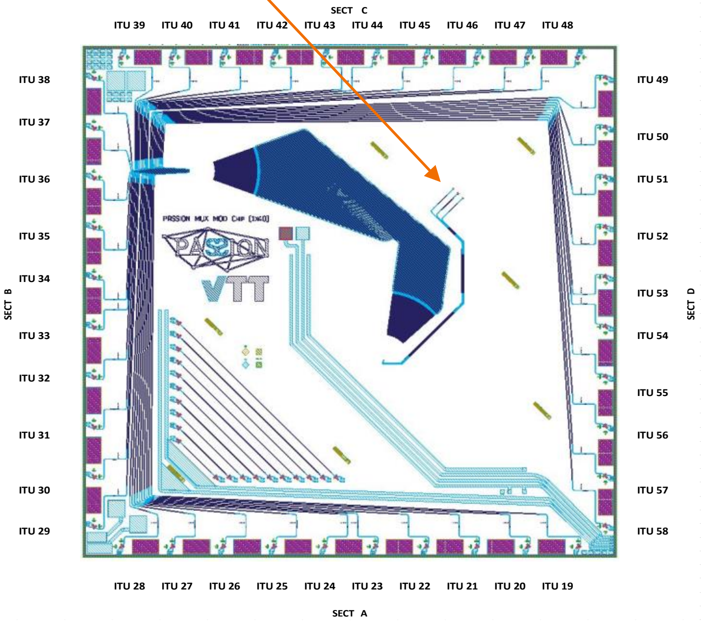
40-channel multiplexer on 3 µm SOI

- 1-3 dB loss in the arrayed waveguide grating (AWG)
- 20x20 mm SOI chip size limited by the VCSEL drivers (AWG <10 mm^2)



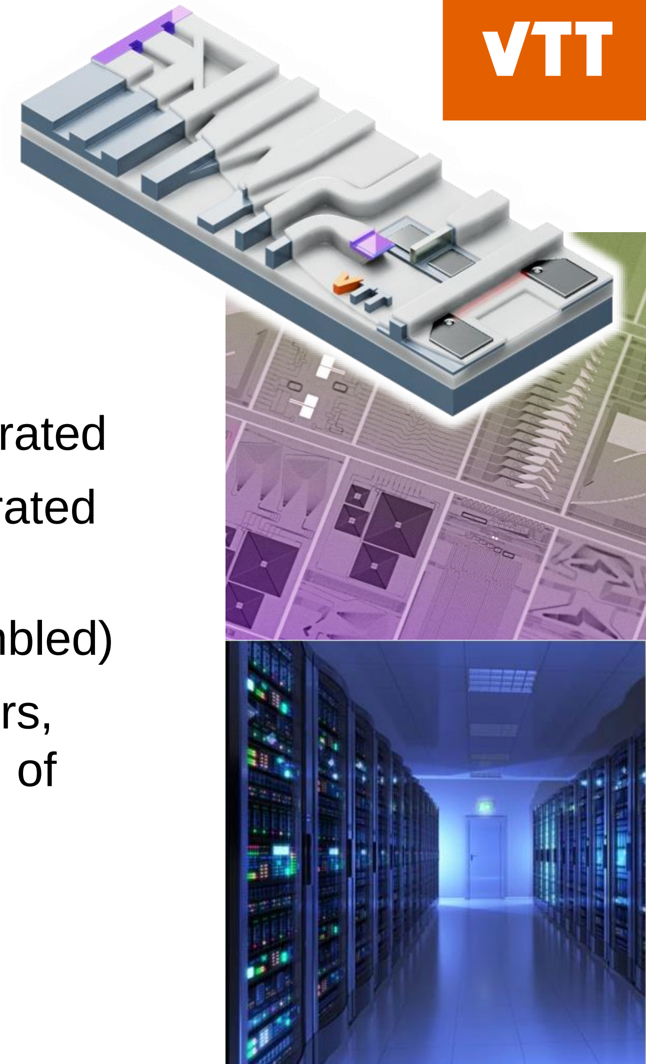


Exit port(s)



Conclusions & outlook

- 3 µm SOI PICs support ultra-broadband and polarization independent operation with low losses and small footprint
- Ultra-low propagation loss of 4 dB/m was demonstrated
- Monolithic 40 GHz Ge photodiodes were demonstrated
- Hybrid integration of directly-modulated VCSELs aims for 2 Tb/s tranceivers (prototype being assembled)
- Future goals include ultra-fast plasmonic modulators, monolithic optical circulators and hybrid integration of 100 Gbaud modulators



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NOIMO

RAPSI
PICAP
OPEC

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