InP Membrane Heterogeneous Integration

Yuqing Jiao

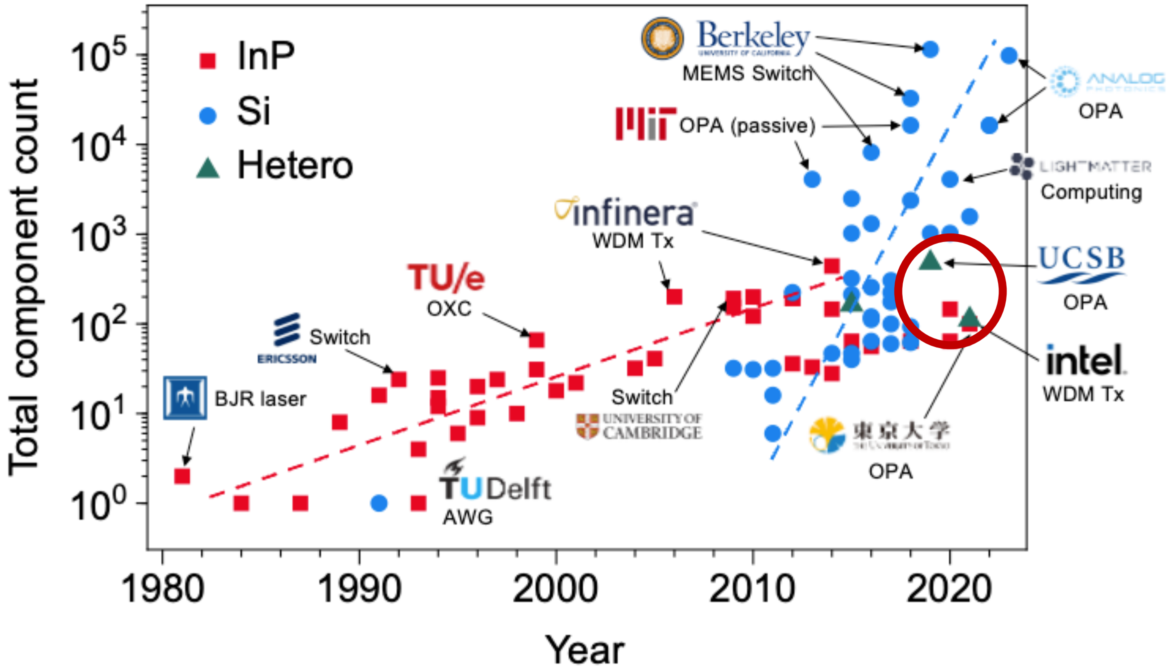
Electrical Engineering, Photonic Integration

Outline

- Density bottleneck in photonic integrated circuits
- Our technology on an InP membrane
- Miniaturization and efficiency boost in active devices
- Summary

Photonic Integration

- Density bottleneck is not solved by introducing Si photonics alone
- Active components limit the density in heterogeneous circuits

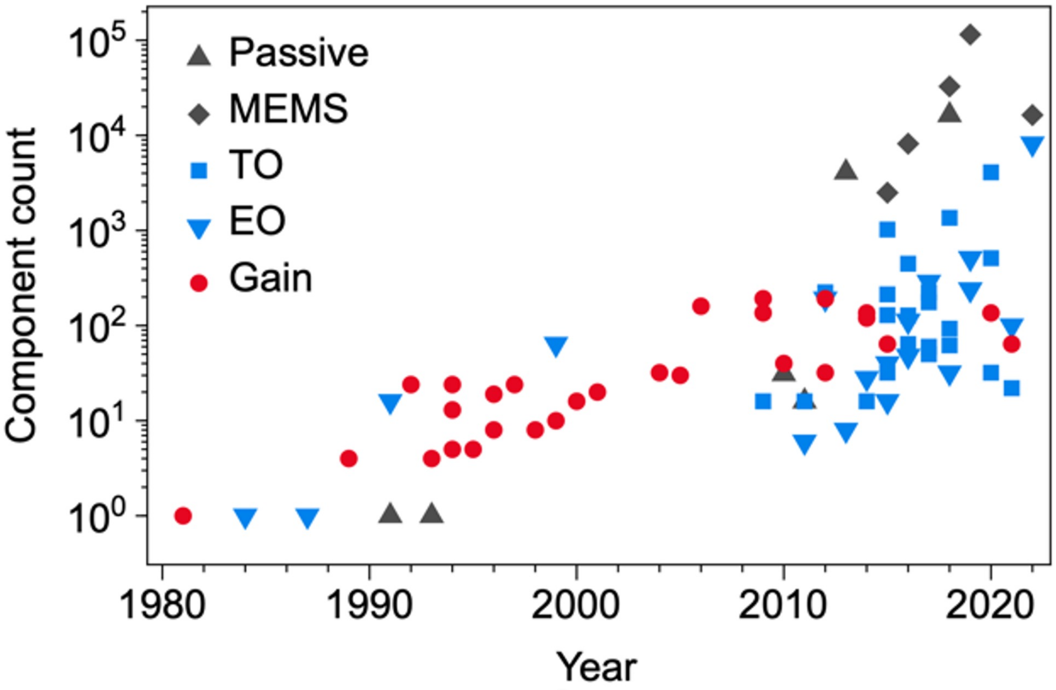


Passive

Active/passive

* Simple light routing components (waveguides, splitters, tapers, etc) not counted

Photonic Integration



- Density boost driven by passives and MEMS optics
- Gain and EO elements remained relatively bulky

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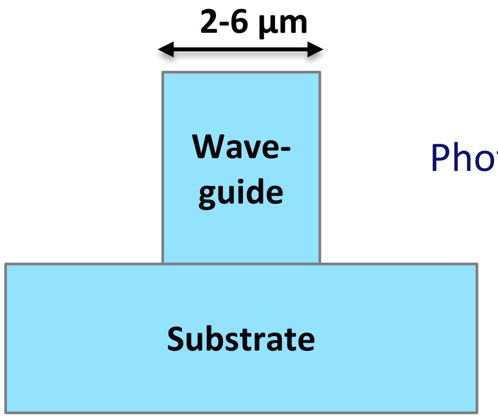
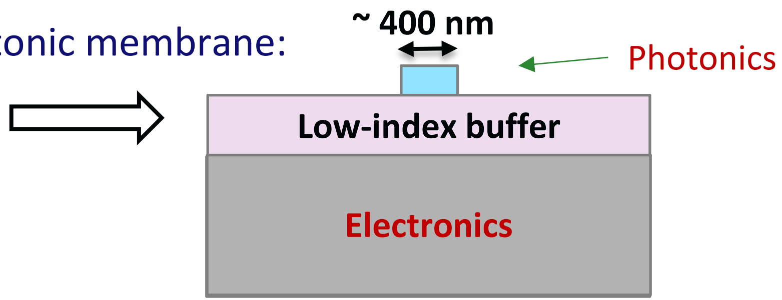
Photonic Integration in a membrane

- InP membrane: InP amplifiers/lasers + SiPh-like nanowire waveguides
- Wafer-scale assembly with electronics

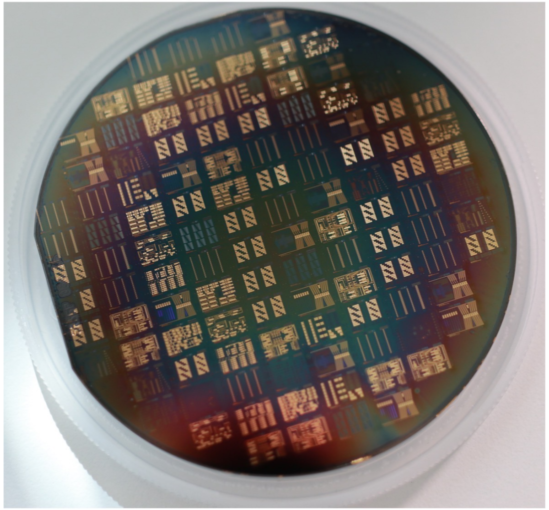


Current industrial approach

Photonic membrane:

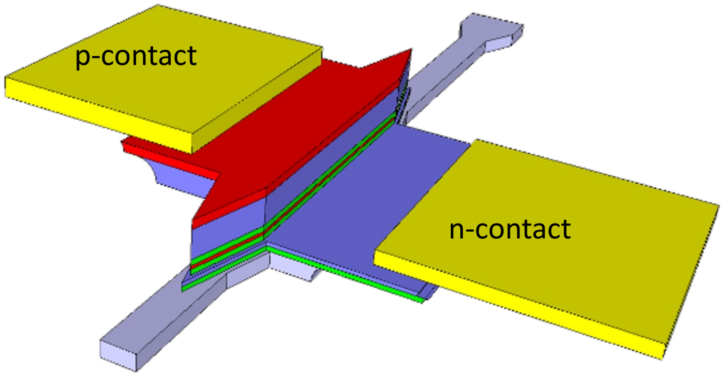


(M. Smit, plenary talk)

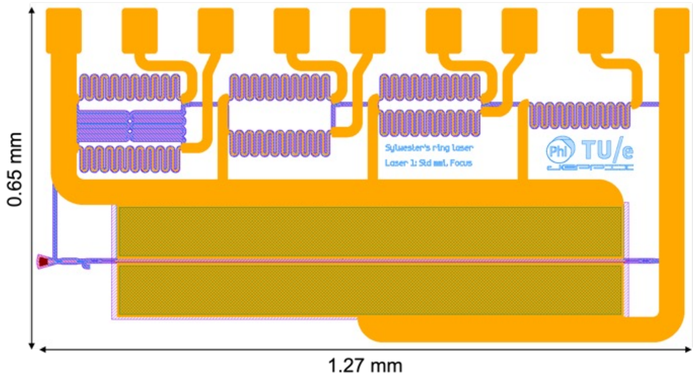


Lasers on nanophotonic waveguides

- S-shaped amplifier/laser for balanced confinement vs power handling
- Improve optical mode matching – very short tapers
- No critical alignment (lithography overlay accuracy)



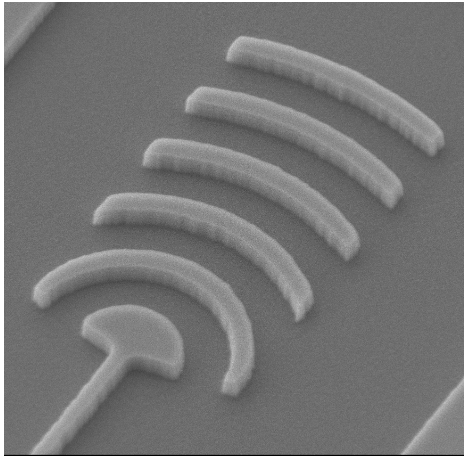
waveguide
400 nm × 300 nm



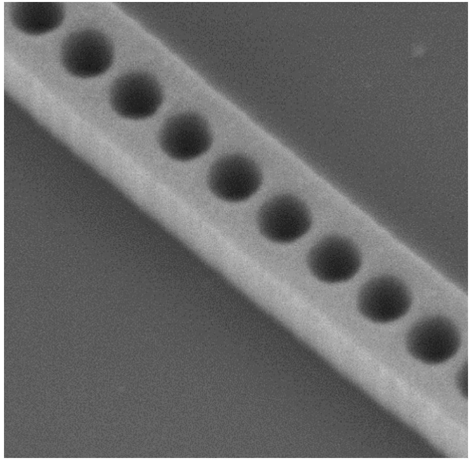
Example Compact tunable laser on membrane
This Session @ 15:15 – 15:30

physica status solidi (a), vol. 217, p. 1900606, 2020.

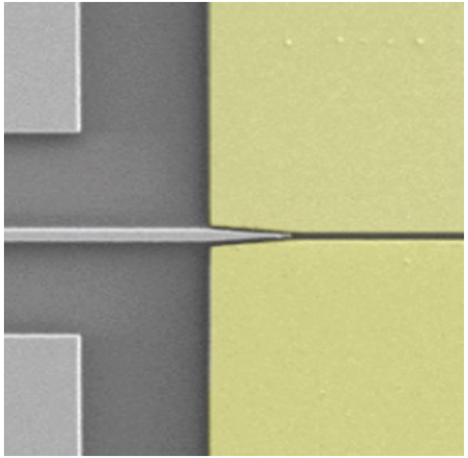
Nanophotonic passive library



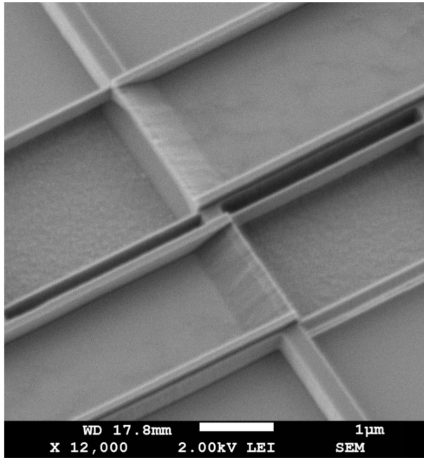
Grating antenna



Photonic crystal



Plasmonics

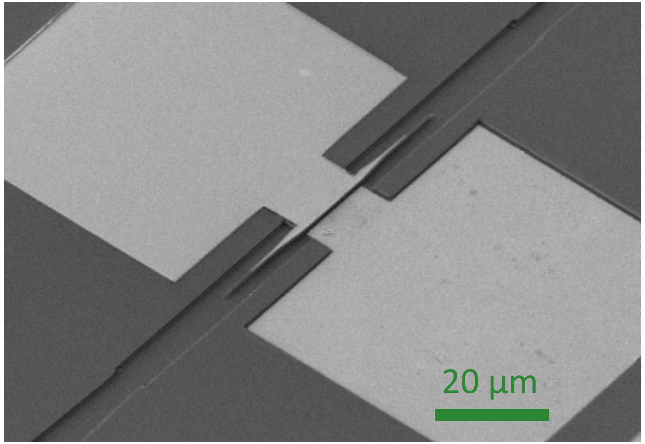


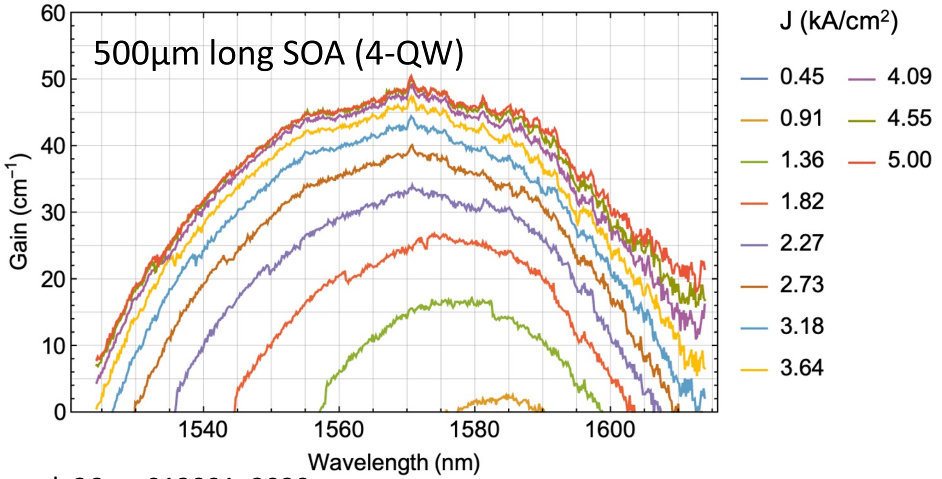
Polarization rotator

TE/TM conversion in 4 µm length
This Session @ 15:00 – 15:15

Amplifiers are intrinsically power hungry

- ~ 200 dB/cm net modal gain in 4-QW SOAs
- Wall-plug efficiency (WPE) typically < 1%
- High electrical power supply to amplifier weak optical signals
- Improvements exist at device level: optimizing QW materials, electrical structure, etc





Semiconductor Science and Technology, vol. 36, p. 013001, 2020.

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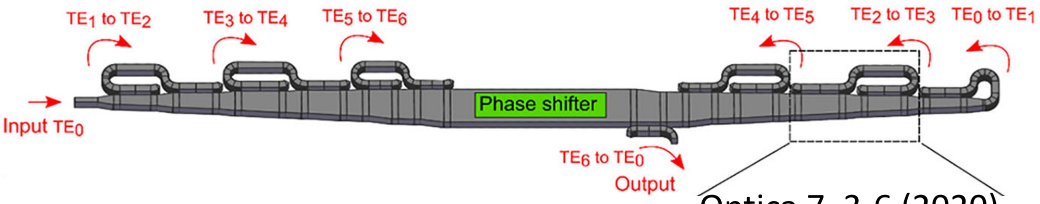
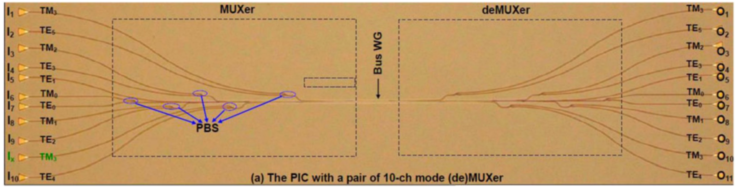
Circuit-level method: Folding the device by MDM

- Non-resonant light recirculation has been used to boost efficiency in linear phase shifters
- Thermo-optic phase shifter

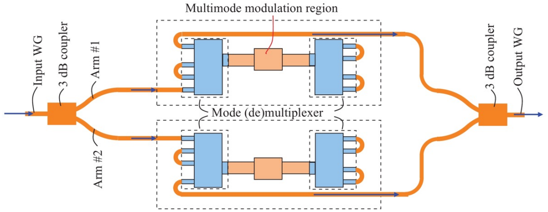


Optica 7, 3-6 (2020)

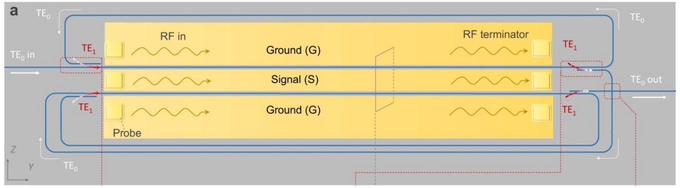


Laser & Photon. Rev. **12**, 1700109 (2018)

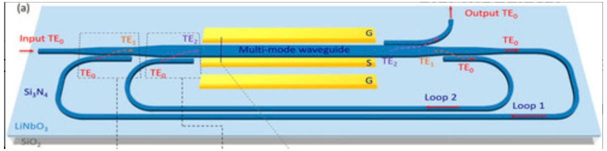
- Electro-optic phase shifters,



J. Semicond. 39 061009 (2018)



Communications Physics 6: 17 (2023)



APL Photonics 7, 106102 (2022)

- Its use in nonlinear devices (SOAs, EAMs) is not studied: investigated for first time in this work

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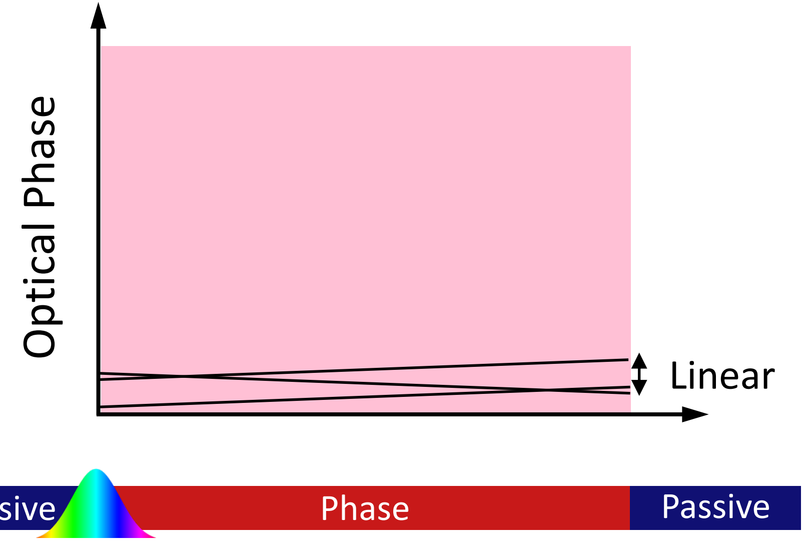
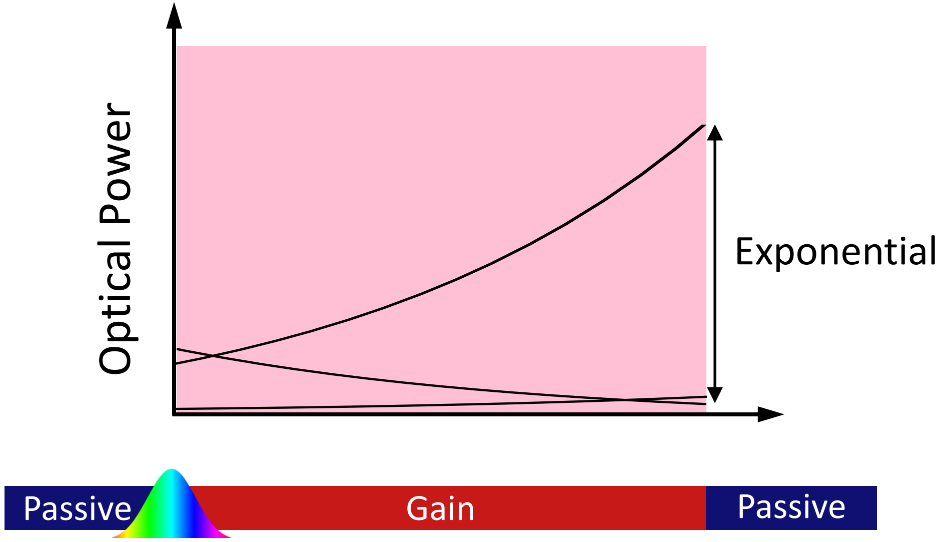
Multi-pass: linear vs nonlinear



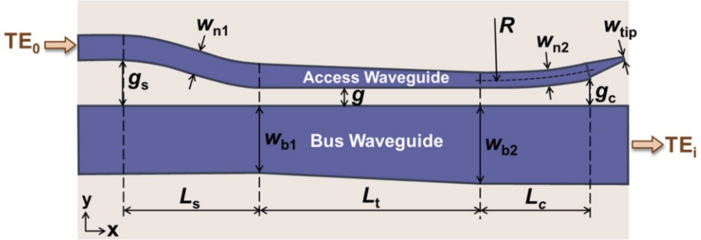
N-pass: N times enhancement

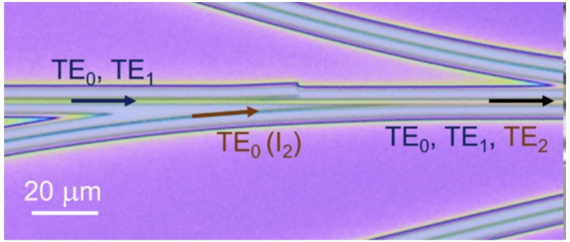


N-pass: >> N times enhancement

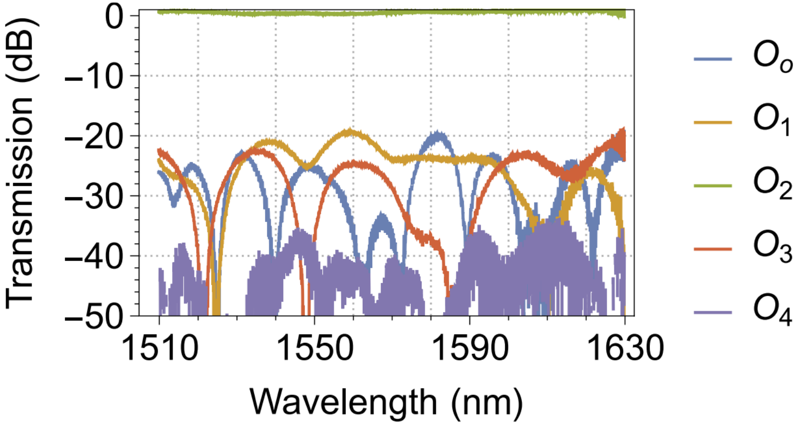
Fab tolerant mode (de)multiplexers in InP membrane

- First mode multiplxer (5 modes) on InP
- Broadband (~ 100nm)
- EL < 1 dB, XT < -14 dB with 50nm width variation
- InP offers high fab tolerance due to moderate index contrast





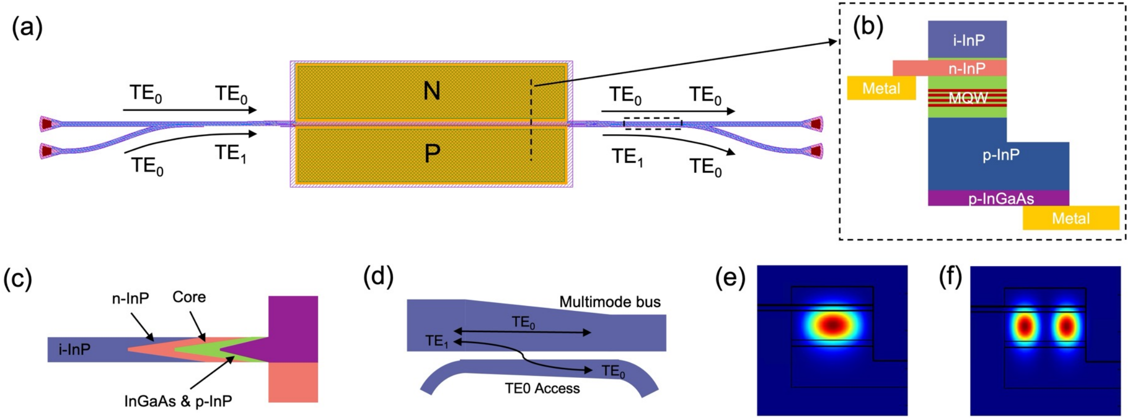
Example: TE2 signal at 20nm width offset

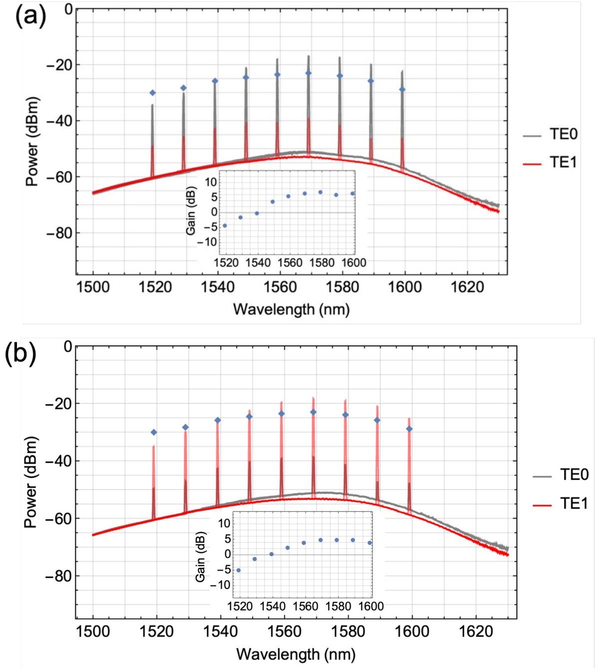


Optics Letters, vol. 47, pp. 4004-4007, 2022.

Mode multiplexing in membrane SOAs

- Combining mode multiplexers and amplifiers made possible InP membrane technology
- TE_1 experiences slightly lower gain than TE_0





arXiv:2303.07485
presented in CLEO 2023

Boosting efficiency of SOAs

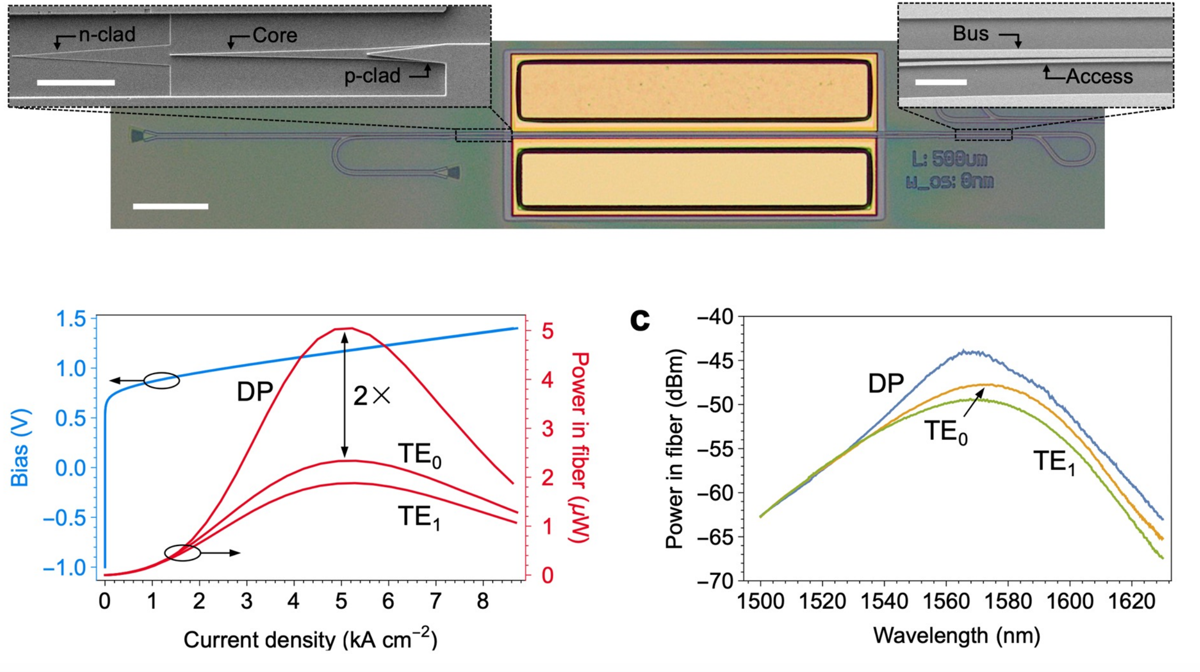
Non-resonant 2-pass SOAs based on mode multiplexing (patent pending):

- Low-crosstalk in the MDM coupler suppresses resonance;
- Gain boosted without increase in pump current, and/or
- "Halved" footprint and pumped energy for the same gain.

arXiv:2303.07485
presented in CLEO 2023

Boosting efficiency of SOAs

2-pass amplified spontaneous emission:



arXiv:2303.07485
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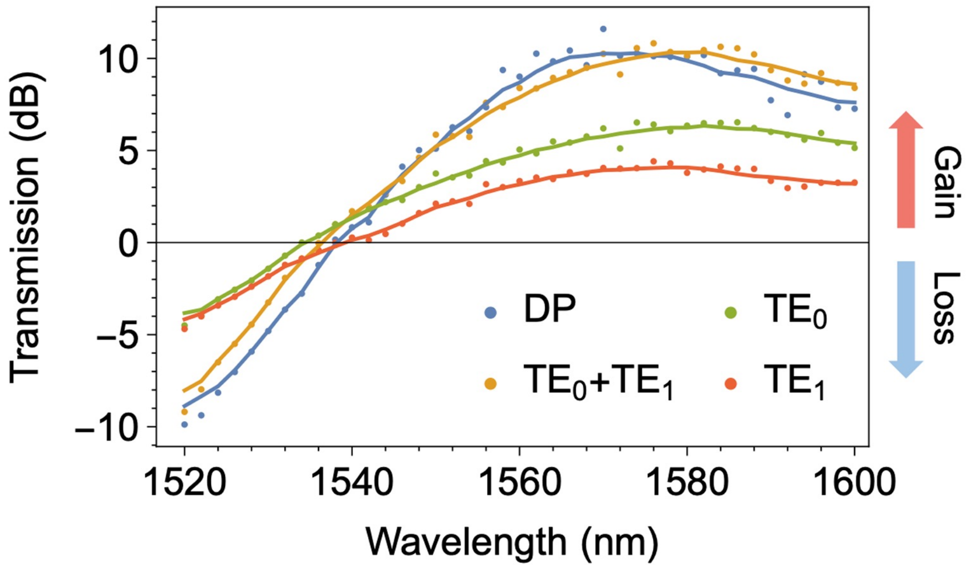
Boosting efficiency of SOAs

2-pass net modal gain (500um long SOA at 4.1 kA/cm^2):

- Gain boosted from 6.2 dB for single pass to 11.6 dB (87% enhancement)
- Absorption (as EAM) also boosted as seen in 1520-1540nm region
- Universal circuit-level method applicable to any PIC platform



arXiv:2303.07485
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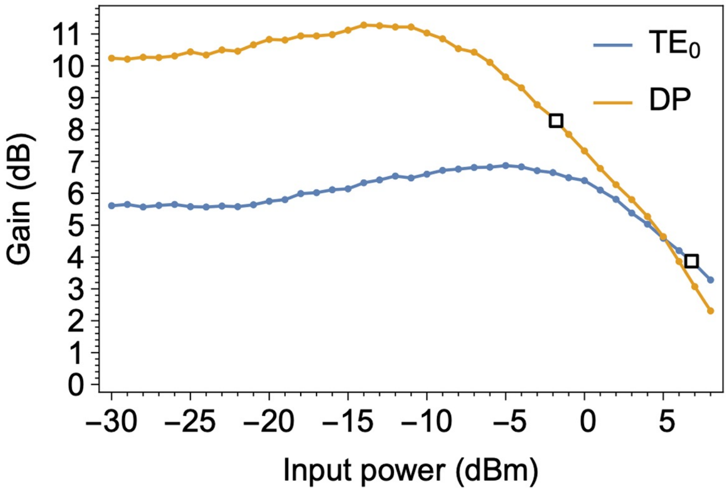
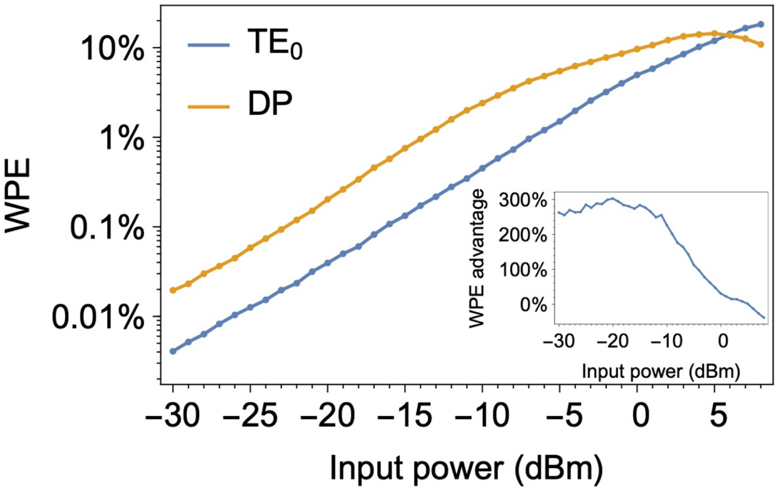
Boosting efficiency of SOAs

Saturation is earlier for 2-pass than 1-pass;

Significant advantage for low input powers (which is the case for most telecom, datacom and switching applications): Wall-plug efficiency (>300% enhancement)





arXiv:2303.07485
presented in CLEO 2023

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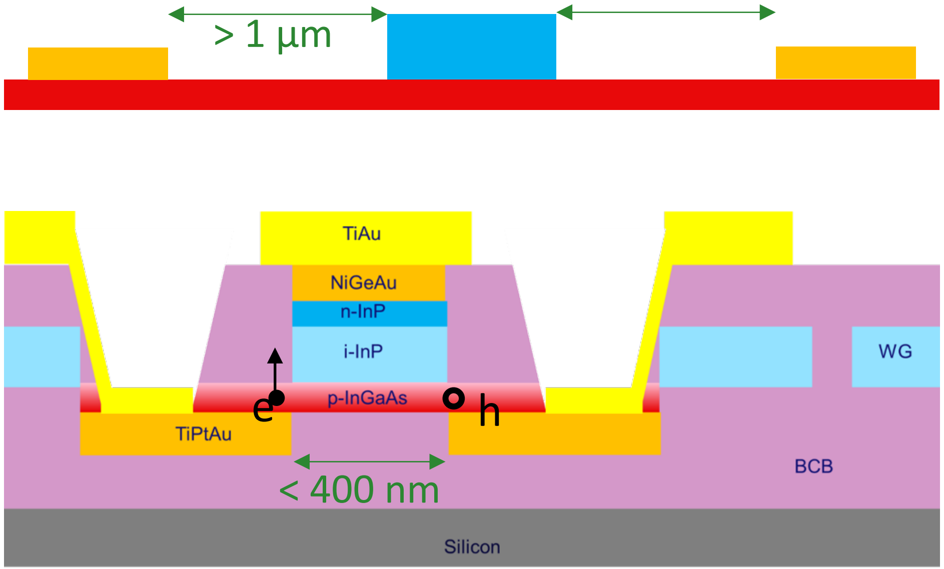
>110 GHz photodiode

Conventional design

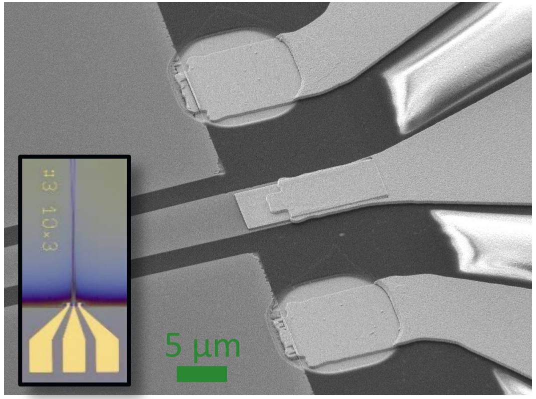
Our design

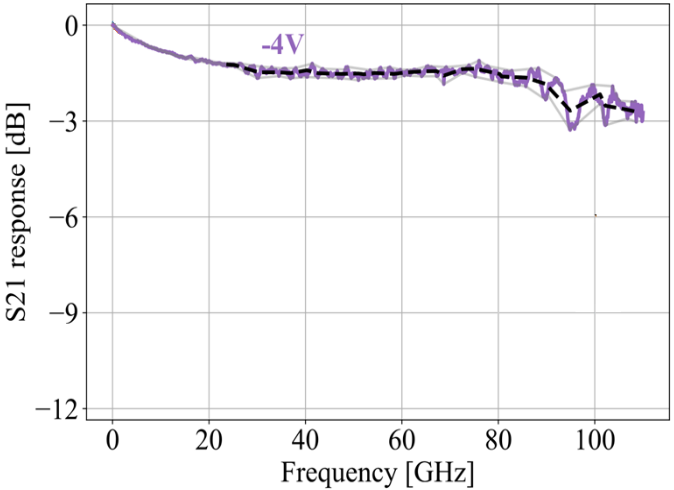
Closer metal contacts without loss compromise

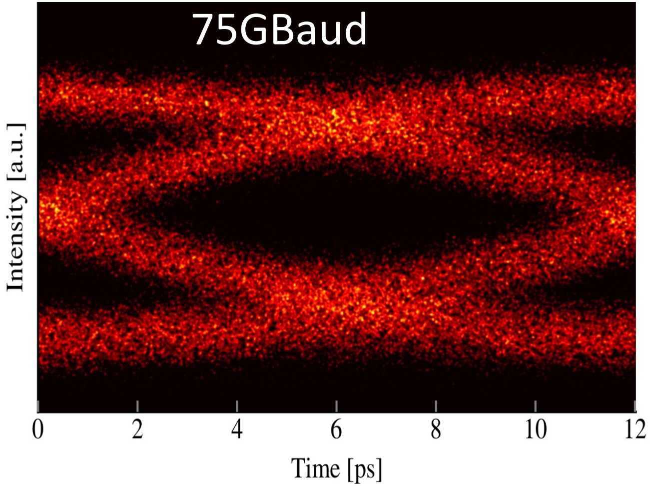


IEEE JSTQE vol. 28, pp. 1-10, 2022.
CLEO 2023 invited

>110 GHz photodiode







Micron-square footprint: 5 x 2 micron^2

InP membrane platform for density and speed scaling

IEEE JSTQE vol. 28, pp. 1-10, 2022.
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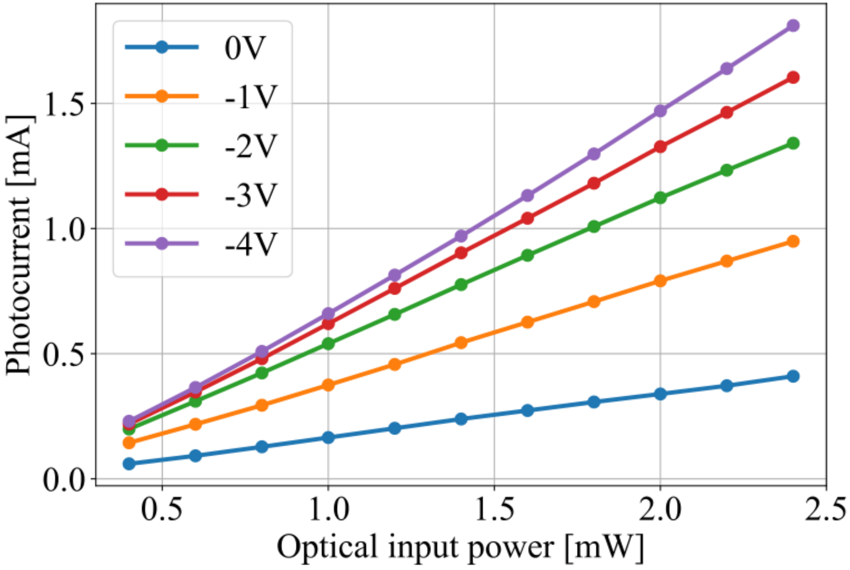
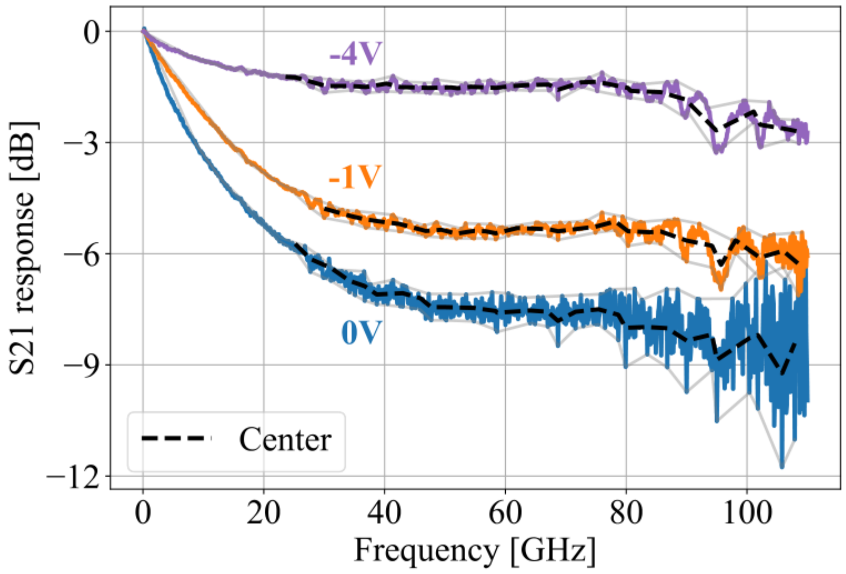
>110 GHz photodiode





0.6 - 0.7 A/W responsivity
5 x 2 micron^2 photodiode area

No band-smoothing layers in this device; resolved in a parallel work

IEEE JSTQE vol. 28, pp. 1-10, 2022.
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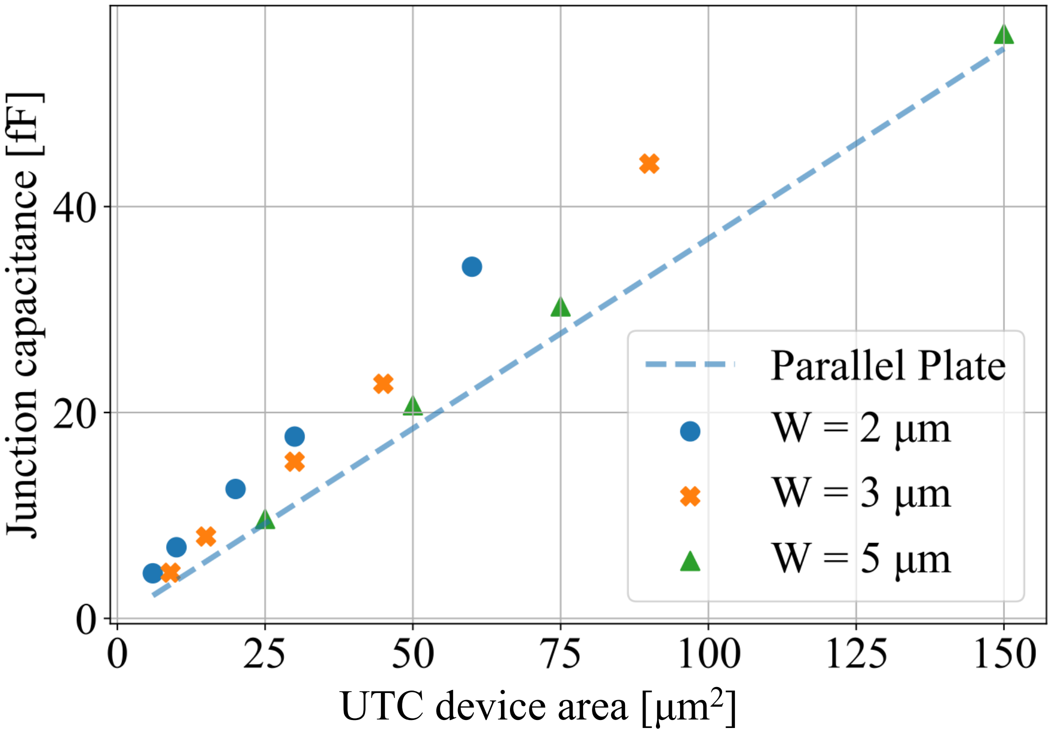
Carrier diffusion limited design



Deviation from parallel plate model for 2 & 3 µm wide devices may be caused by a parasitic capacitance

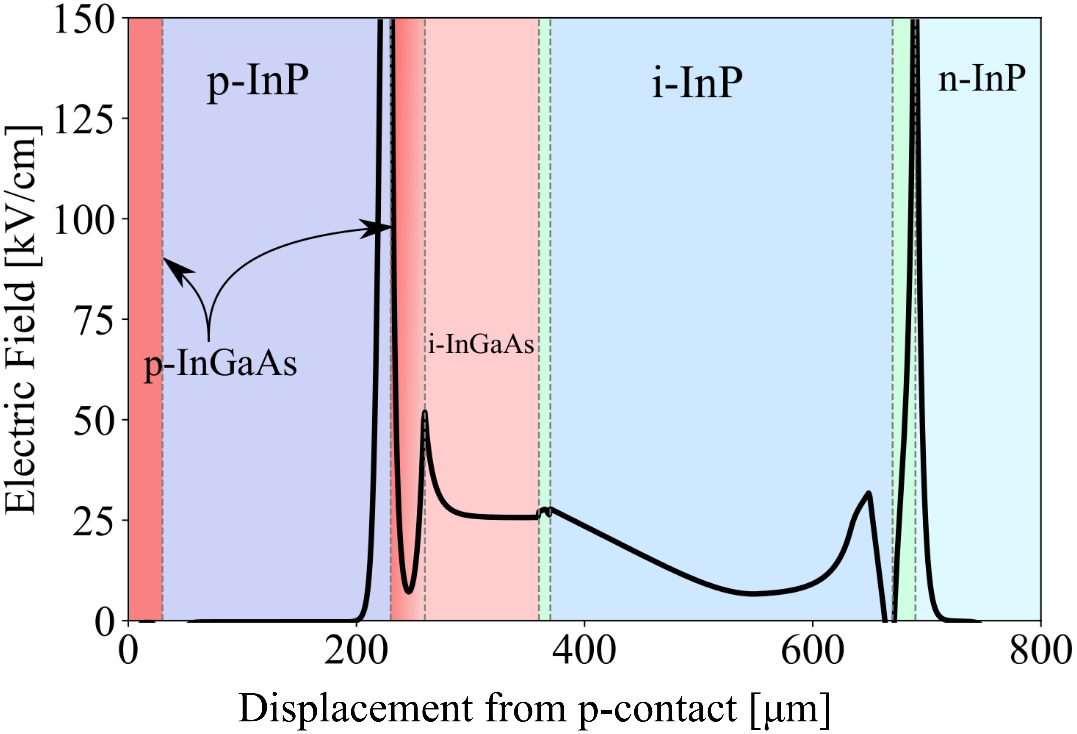
Leakage of the electric field around the edges of the structure.

Junction capacitance as low as 4.4 fF is achieved

Series resistance of the same device of 6.5 Ω

IEEE JSTQE vol. 28, pp. 1-10, 2022.
CLEO 2023 invited

Route to 200 GBaud UTCs

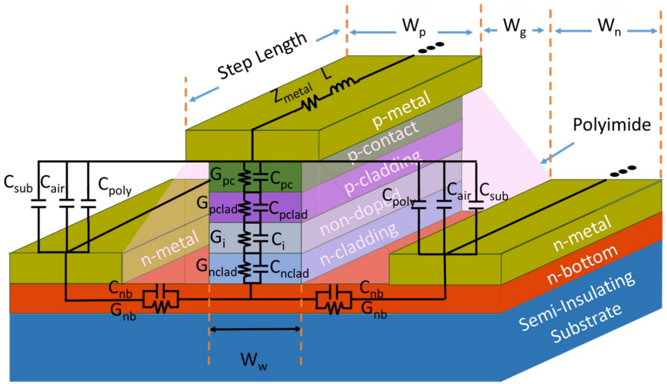


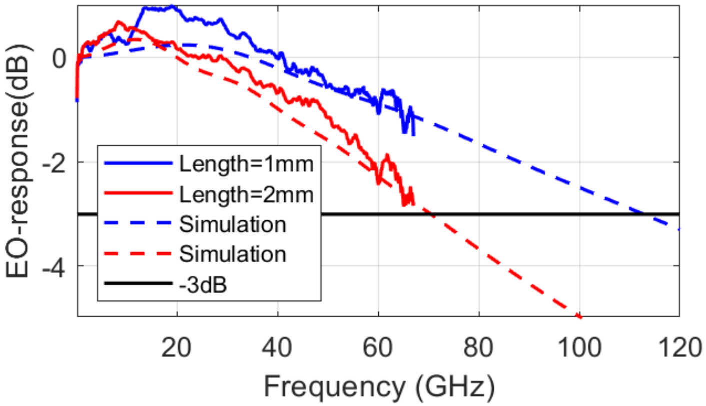
Transit time further reduced by separating the absorption layer into an undoped and p-doped region

Graded doping to ensure electron overshoot velocity is reached

The simulated electric field profile at −0.5 V bias and at 1 mA sufficiently high to ensure overshoot velocity.

High-density 100GHz-class EO modulators



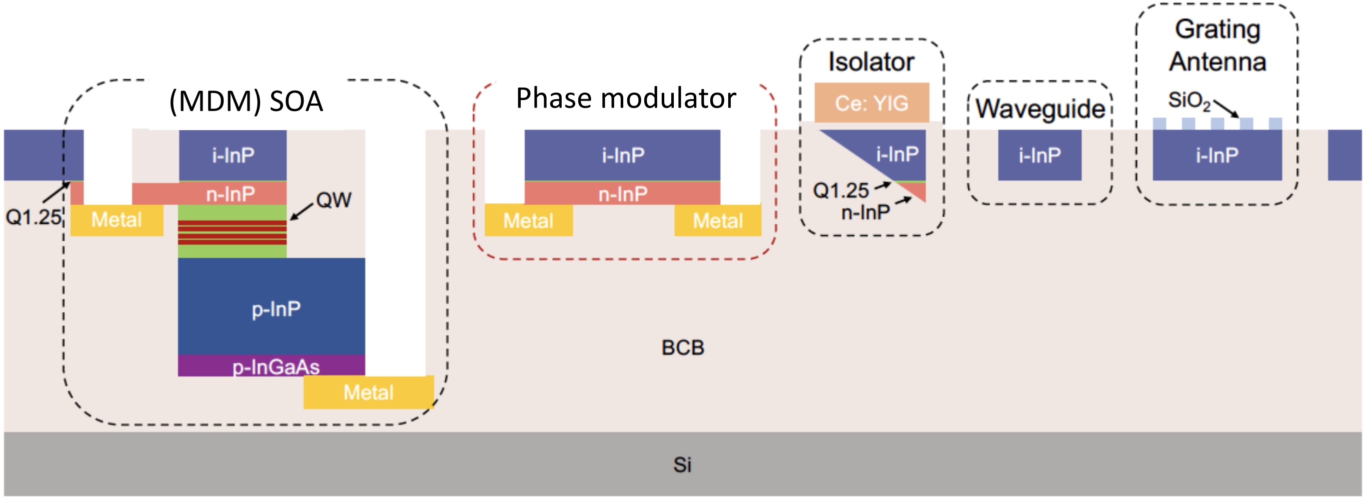


Demonstrated on semi-insulating InP substrate, but transferrable to membrane

For details please attend:
Next session in this room @ 17:00 – 17:15

Laser and nanophotonics in one process flow

- An active-passive platform realized with a single process flow
- Eliminate the need of assembly or bonding for external light source



Summary

- Active-passive photonic integration on an InP membrane
- InP membrane nanophotonics enables compact and highly efficient gain and EO devices
- Circuit-level method widely applicable to any PIC platform

JePPIX

Nanolab @ TU/e

Gravitation

EU H2020