Photonics Integrated Circuits for Free Space Communications

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Outline

- **1. Background**
  - 1.1 Free space optical communications
  - 1.2 Photonic integrated circuits
- **2. Epi design**
  - 2.1 Epi structures
  - 2.2 Integration platforms
- **3. OQW-based PIC Transmitter**
  - 3.1 Fabrication process
  - 3.2 PIC characterization
  - 3.3 Free space link
- **4. QWI-based PIC Transmitter**
  - 4.1 Fabrication process
  - 4.2 PIC characterization
  - 4.3 High-power SOAs
- **5. Future work**

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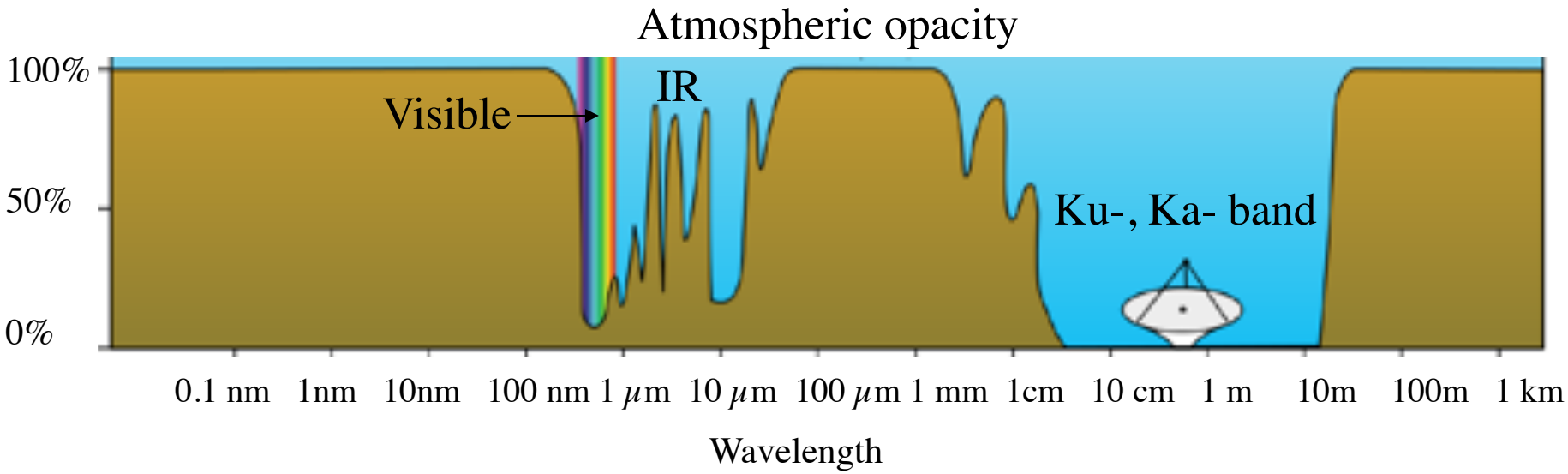
- **1. Background**
  - 1.1 Free space optical communications
  - 1.2 Photonic integrated technologies
- 2. Epi design
- 3. OQW-based PIC transmitter
- 4. QWI-based PIC transmitter
- 5. Future work

1.1 Free space optical communication



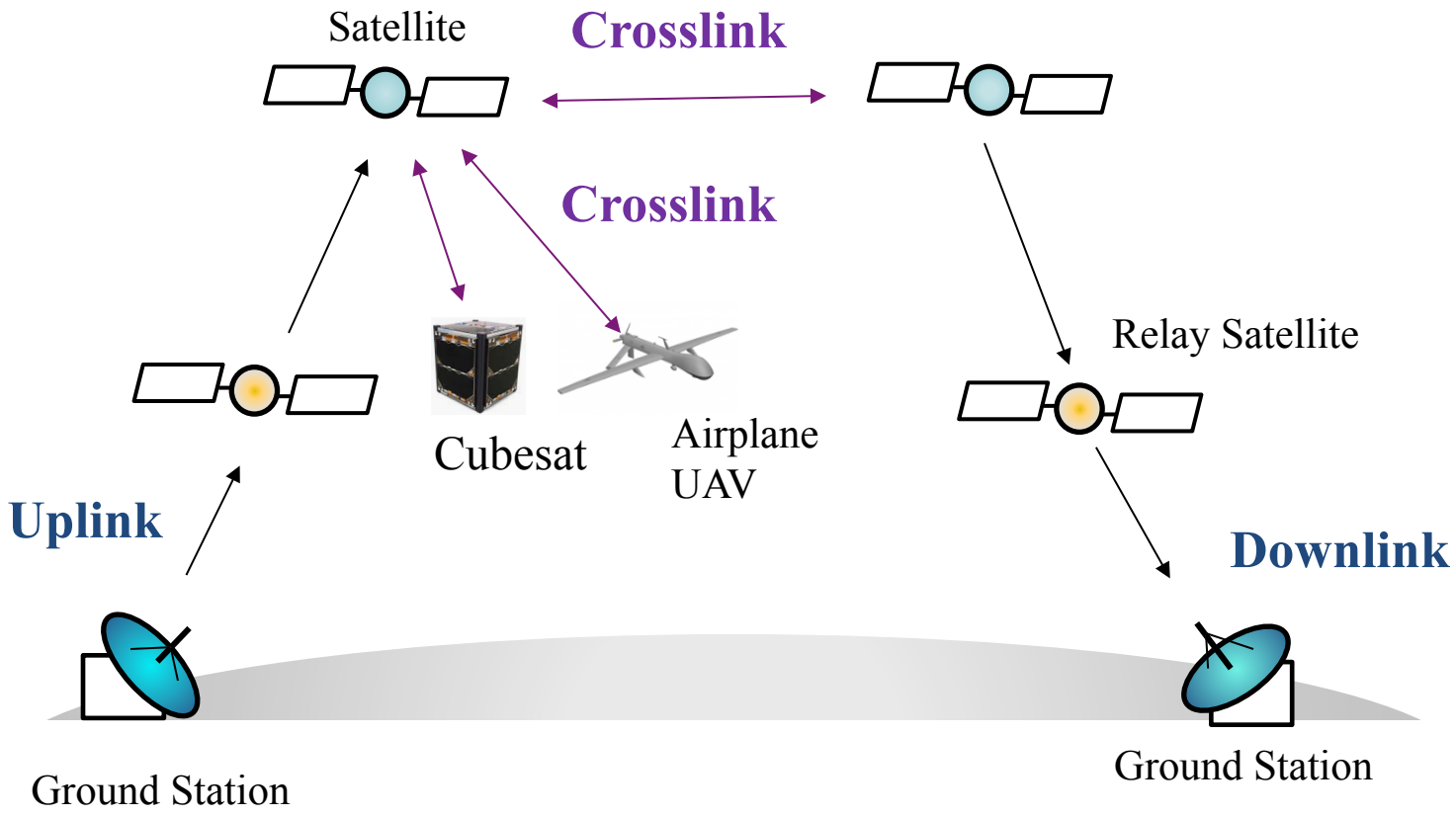
https://gisgeography.com/atmospheric-window/

Optical vs Radio frequencies

- **Higher Data Rate**
- **Unlicensed Spectrum**
- **Easily expandable**
- **Less Power and Mass Requirement**
- **High Security**
- **Dependence on Weather Conditions**

https://swfound.org/news/all-news/2013/06/swf-releases-new-fact-sheet-on-radio-frequency-spectrum-and-satellites
H. Kaushal et. al., IEEE Communications Surveys & Tutrorials. 19 (1), 2017

1.1 Free space optical communication

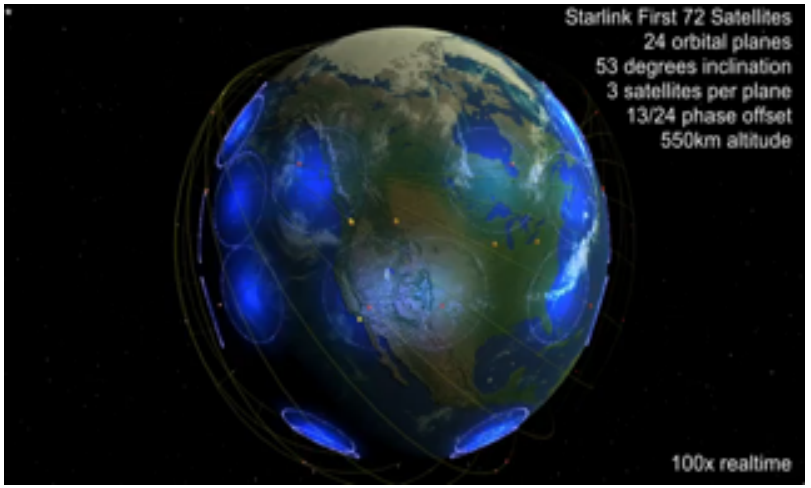


Space optical link architecture

H. Kaushal et. al., IEEE Communications Surveys & Tutrorials. 19 (1), 2017

1.1 Free space optical communication

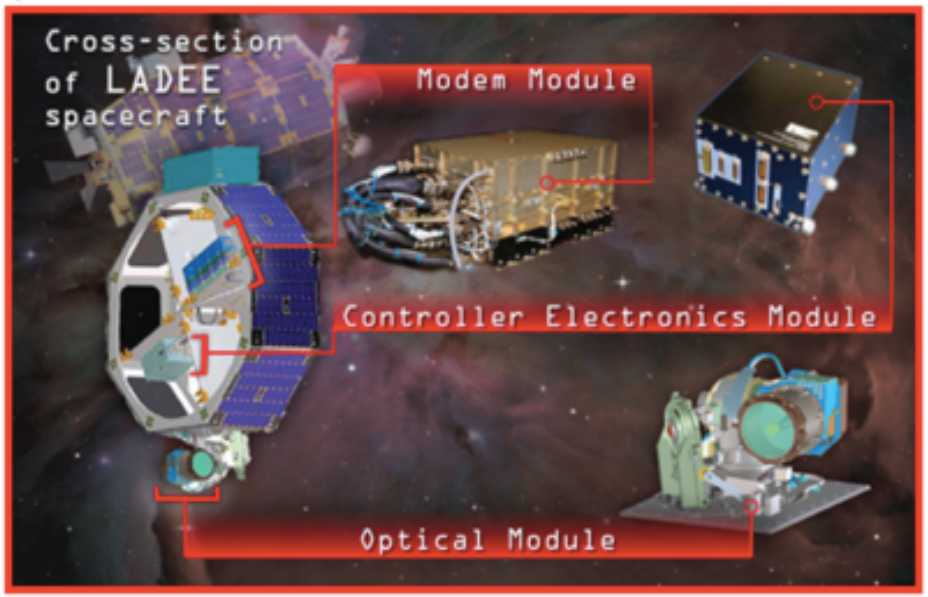
Starlink Satellites by SpaceX



https://www.spacex.com/

- First 60 spacecraft of nearly 12,000 planed
- SpaceX wants to offer internet service after 6 launches
- Plans to complete Starlinks in 2027
- OneWeb, Telesat, Amazon have similar plans

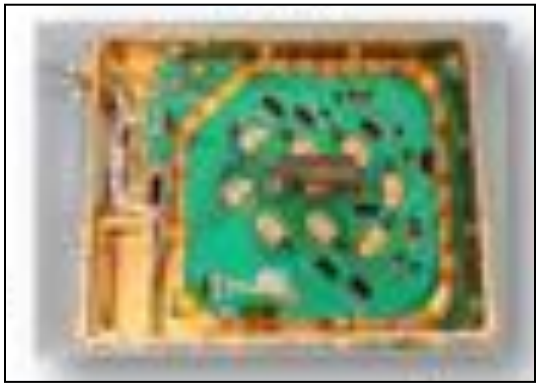
1.1 Free space optical communication



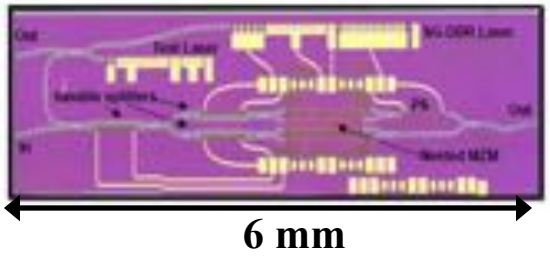
http://llcd.gsfc.nasa.gov

Lunar Laser Communication Demonstration

- Lunar-orbiting spacecraft ←→ Ground
- 20 Mbps uplink / 622 Mbps downlink

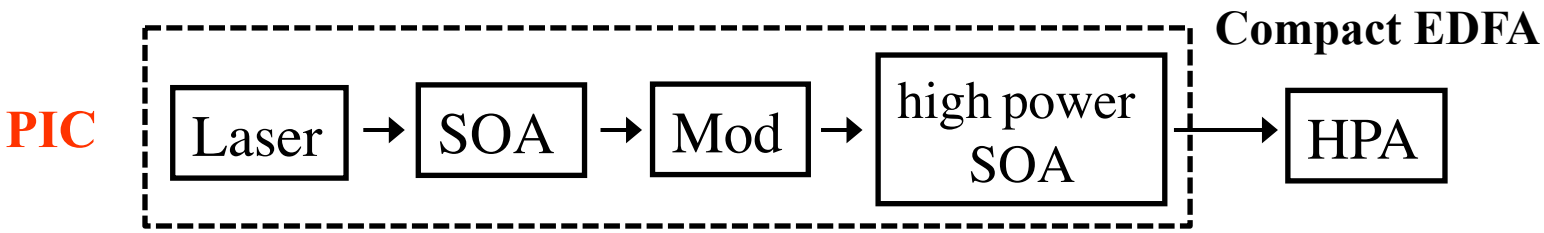


Photonic Integrated Circuits (PICs)



Significantly reduced Cost, Size, Weight and Power (CSWaP)

1.1 Free space optical communication



Crosslinks
100 ~1000 m

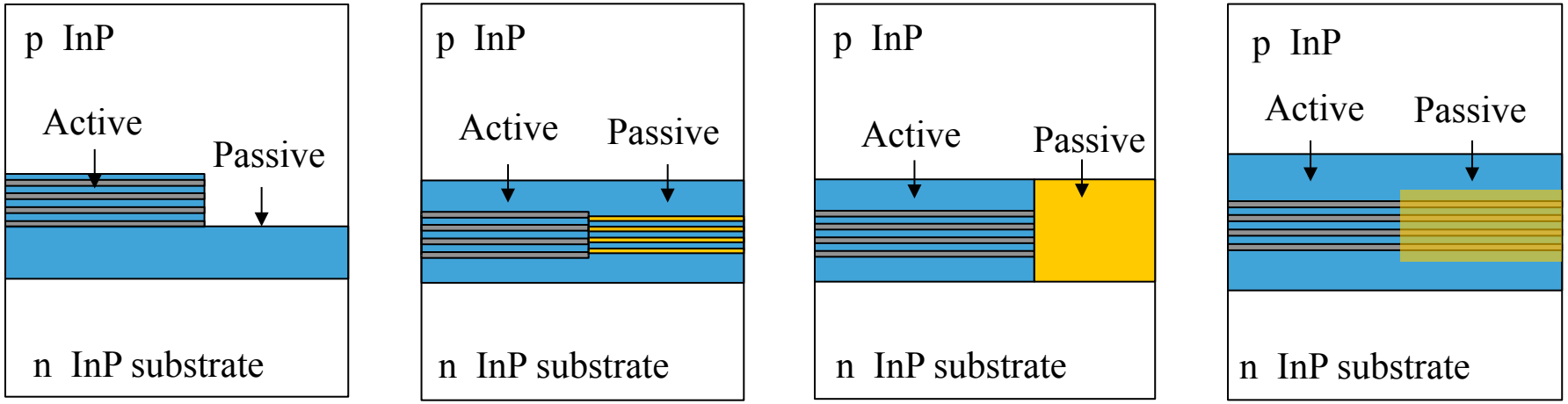
LEO links

Deep space links

- Photonic integration → lower CSWaP
- Higher optical power → longer distance
- Power efficient modulation → increase peak power
- Couple with compact EDFA →very long distance

1.2 Photonic integrated technologies

Integration Platforms for InP PICs



Offset Quantum Well (OQW)

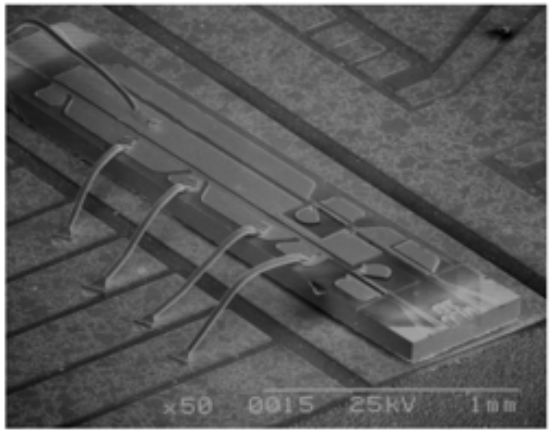
Selective Area Growth (SAG)

Butt Joint Growth (BJG)

Quantum Well Intermixing (QWI)

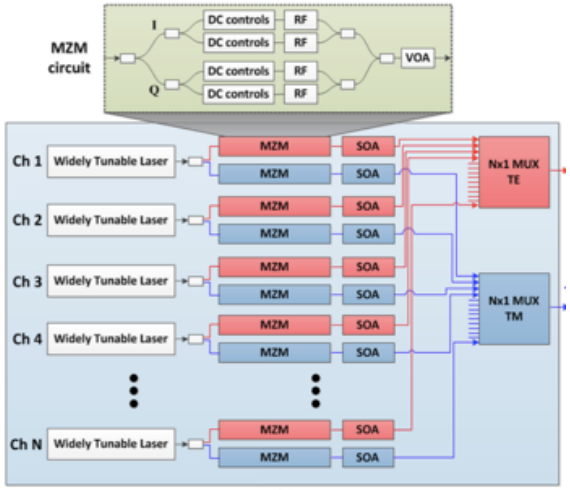
1.2 Photonic integrated technologies

SGDBR Laser/EA-Modulated Transmitter



J. W. Raring et al., J. Lightwave Technol. 23, 80, 2005

Tunable Multi-Channel InP-Based Coherent Transmitter PICs

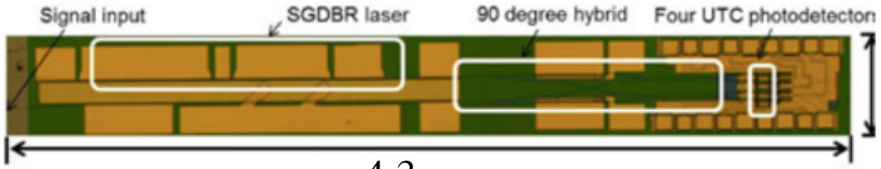


2 Tbps

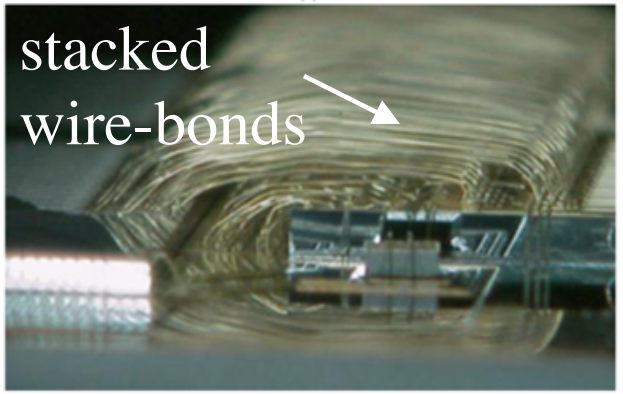
40 wavelength channels

V. Lal et al., J. Lightwave Technology, 35, 7, 2017

InP-based optical-phase-locked loop (OPLL)



H. Park et al. Opt. Express, 20, 26, 2012



1.2 Photonic integrated technologies

Spectral efficiency

⇩

Power efficiency

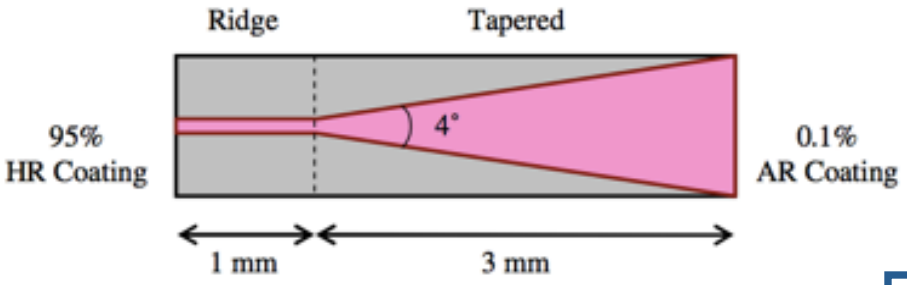
Saturation power in SOAs:

$$P_{o,sat} = \left(\frac{G_0 \ln 2}{G_0 - 2}\right)\frac{A}{a\tau}\frac{h\upsilon}{}$$

$$A = \frac{wd}{\Gamma} \qquad G_0 = e^{[(\Gamma g_0 - \alpha_i)L]}$$

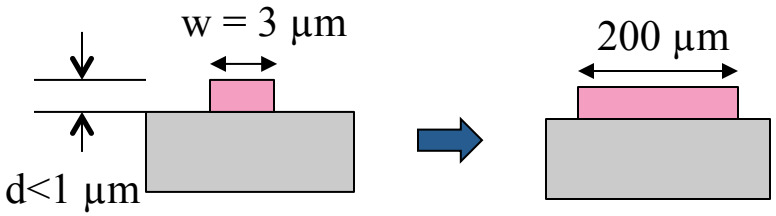
A: mode cross-section area
Γ: confinement factor
G_0: unsaturated gain

Fared waveguide



H. Kwok et al. Proc. Opt. Fiber Commun., 2009

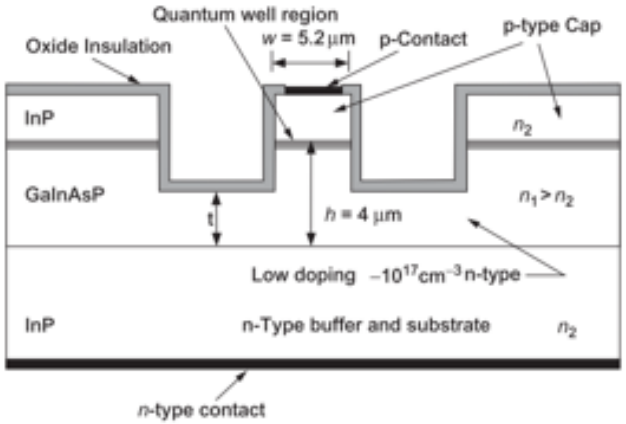
Highly asymmetric mode

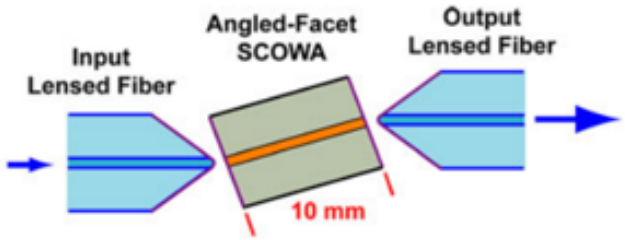


➢ **Beam quality (couple to fiber/space)**

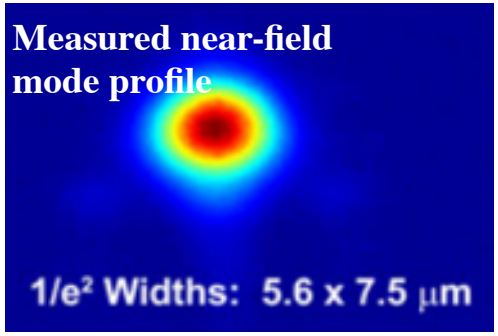
1.2 Photonic integrated technologies

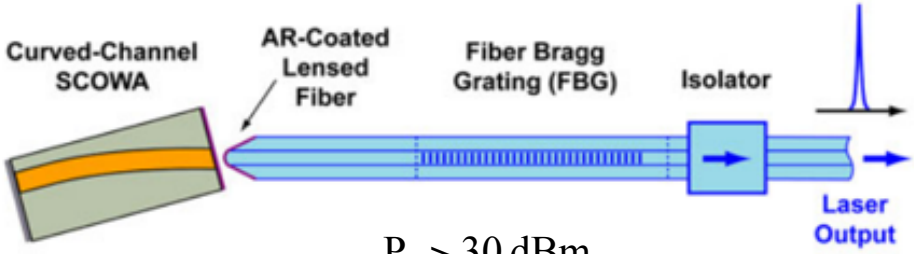
Slab-Coupled Optical Waveguide (SCOWL)





Traveling-wave SCOW amplifier





$P_o > 30$ dBm

Single- frequency SCOW external-cavity laser

P. Juodawlkis et al., JSTQE, 17(6), 2011

➢ **Integration of laser/modulator and SOA**

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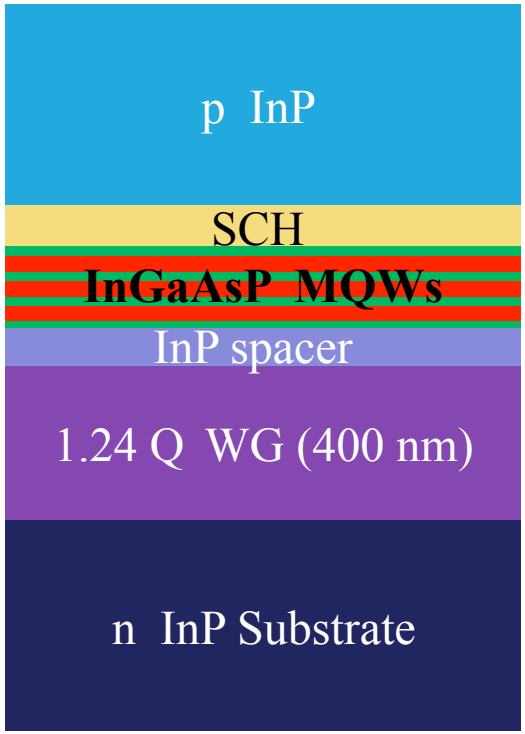
- **2. Epi design**
  - 2.1 Epi structures
  - 2.2 Integration platforms
- 3. OQW-based PIC Tx
- 4. QWI-based PIC Tx
- 5. Future work

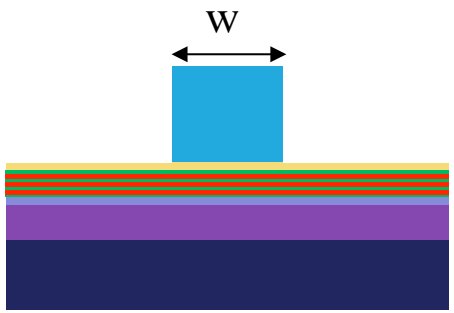
2.1 Epi structures

Epi structure S1

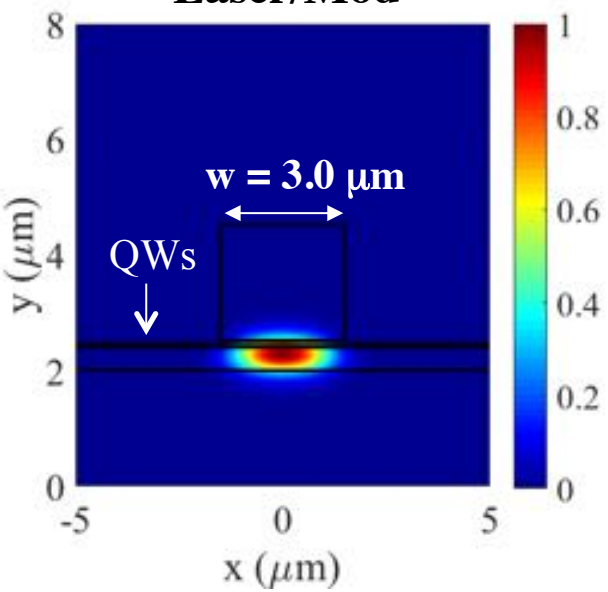


λ = 1550 nm

Surface ridge WG

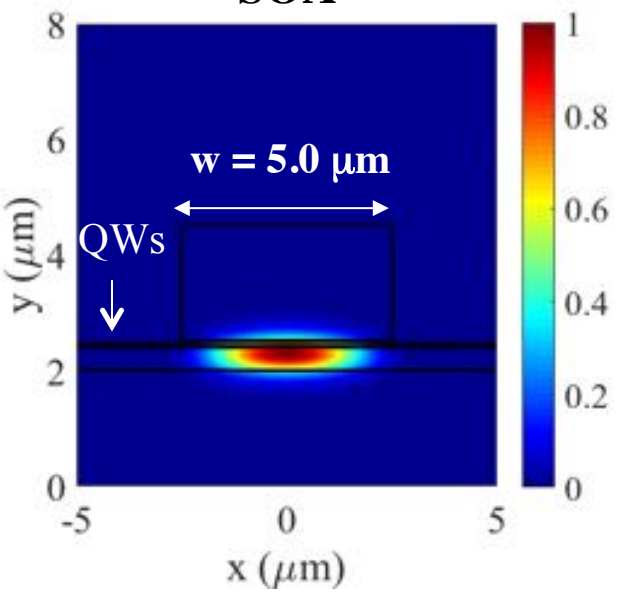


Laser/Mod



A = 2.23 μm² Γ = 4.16%

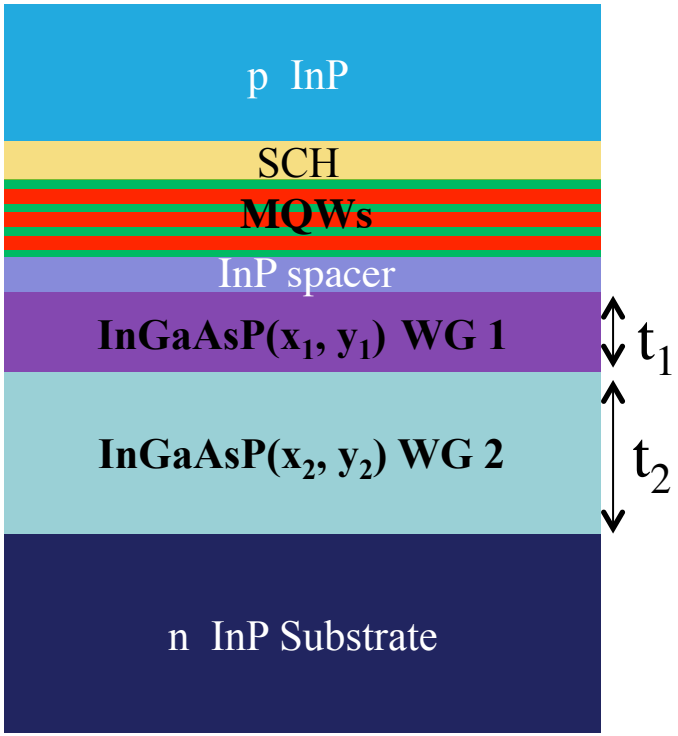
SOA



A = 3.24 μm² Γ = 4.23%

2.1 Epi structures

Epi structure S2



InGaAsP (x, y): $In_xGa_{1-x}As_yP_{1-y}$

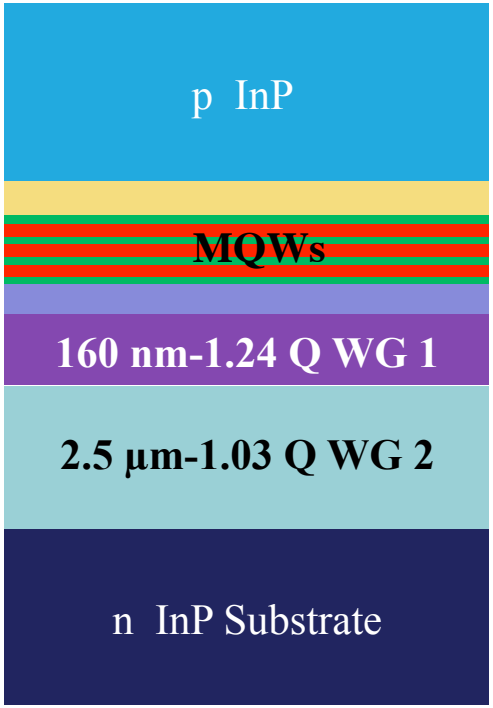
$$P_{o,sat} = \left(\frac{G_0 \ln 2}{G_0 - 2}\right) A \frac{h\upsilon}{a\tau} \qquad A = \frac{wd}{\Gamma}$$

x_1, y_1, t_1
x_2, y_2, t_2
WG structures

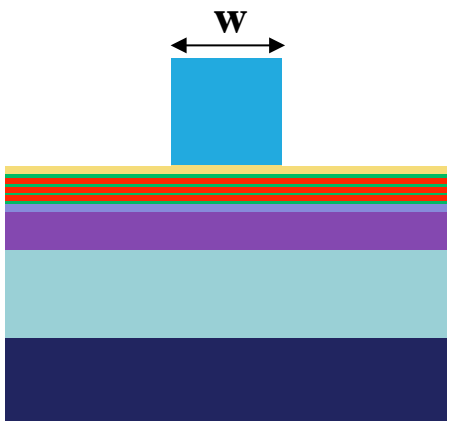
1. Low Γ and large modal area in SOA;
2. Relative high Γ in laser/modulator.

2.1 Epi structures

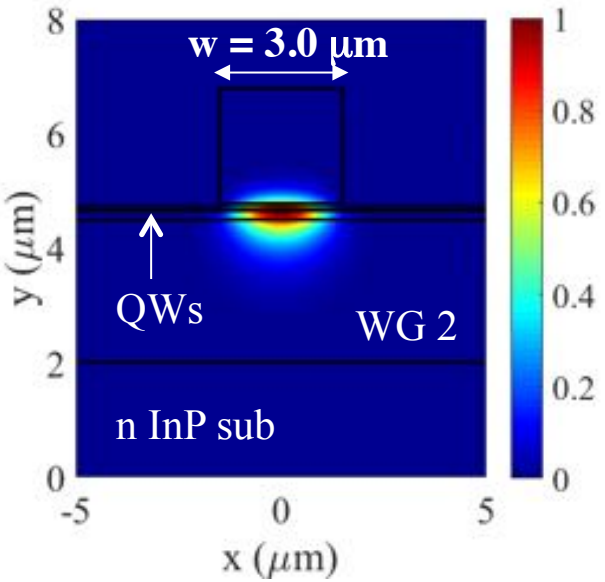
Epi structure S2



Surface ridge WG



Laser/Mod



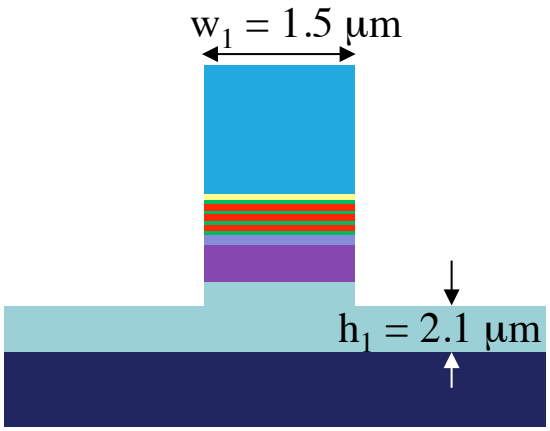
A = 3.37 µm² Γ = 3.73%

Epi structure S1: **A= 2.23 µm² Γ = 4.16%**

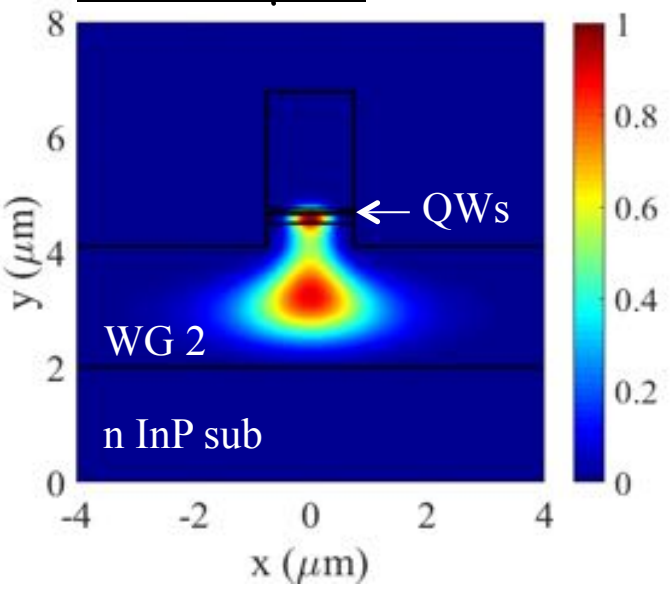
2.1 Epi structures

High-power SOA

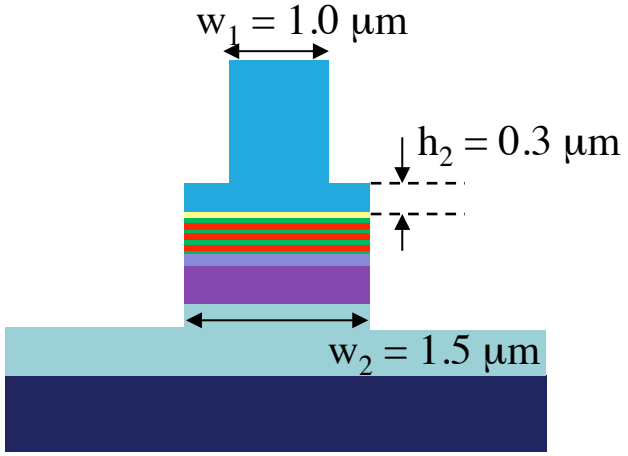
Single ridge WG



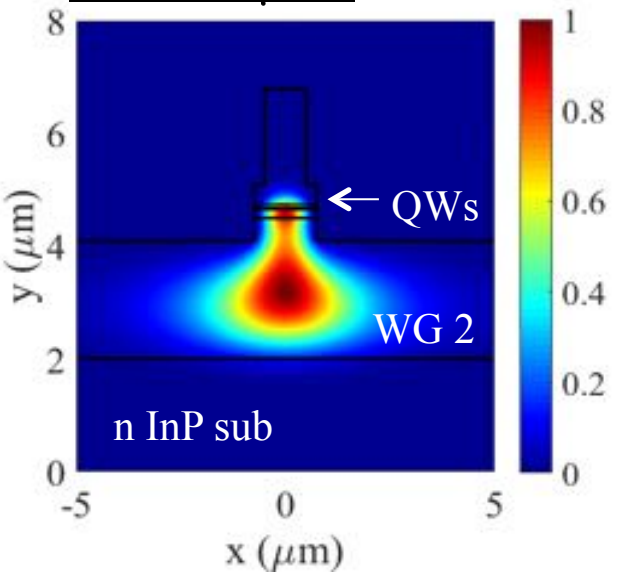
A = 10.97 μm² Γ = 0.41%



Double ridge WG

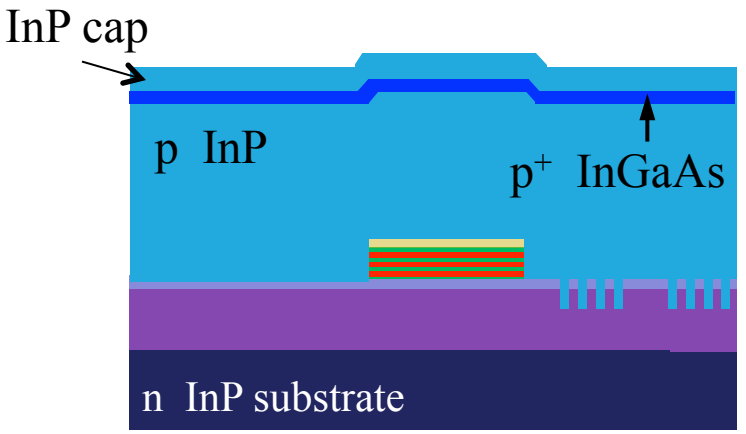


A = 11.37 μm² Γ = 0.35%

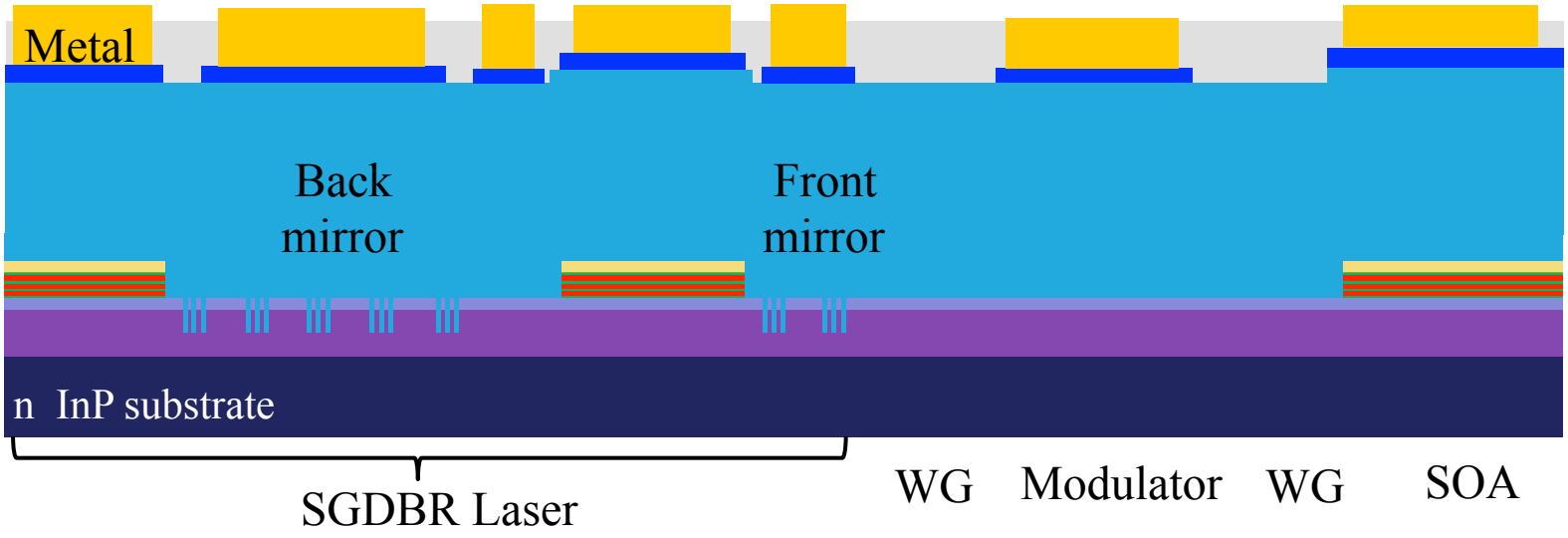


2.2 Integration platforms

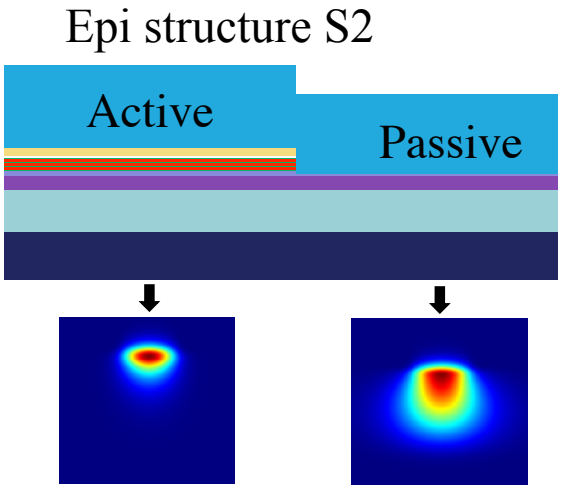
Gen 1 Tx based on OQW



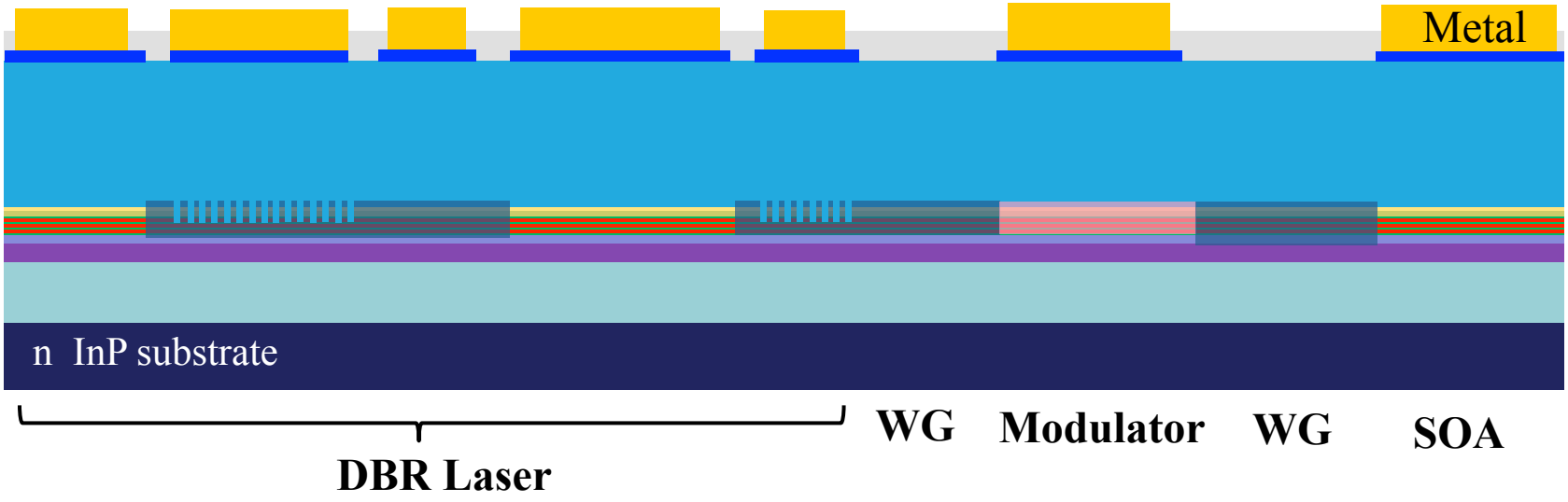
Epi structure S1 after regrowth



2.2 Integration platforms



Gen 2 Tx based on QWI



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  - 3.1 Fabrication process
  - 3.2 PIC characterization
  - 3.3 Free space link
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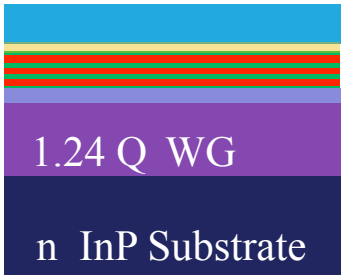
- 5. Future work

3.1 Fabrication process

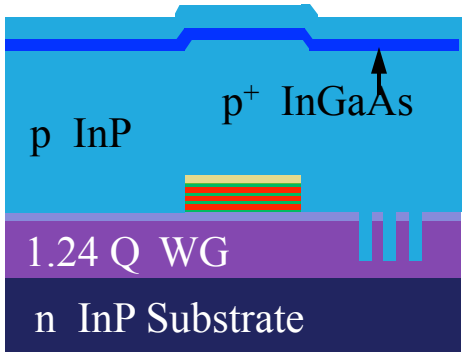
Epi structure S1

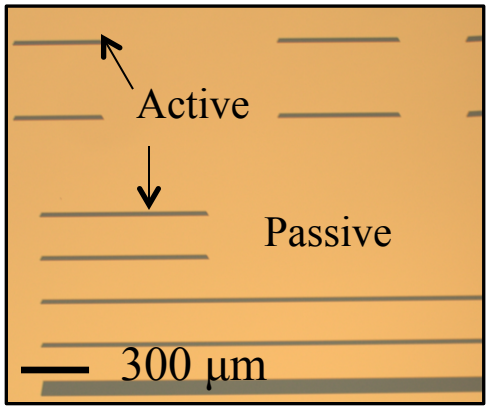


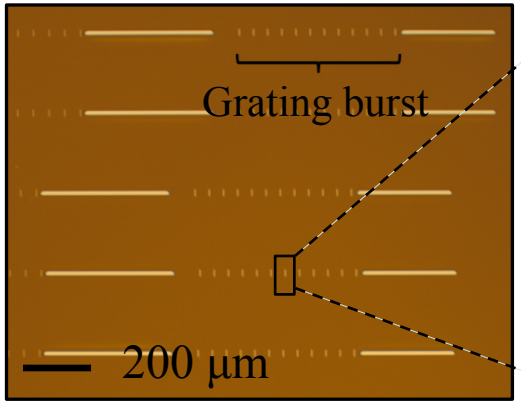
1. Active/Passive

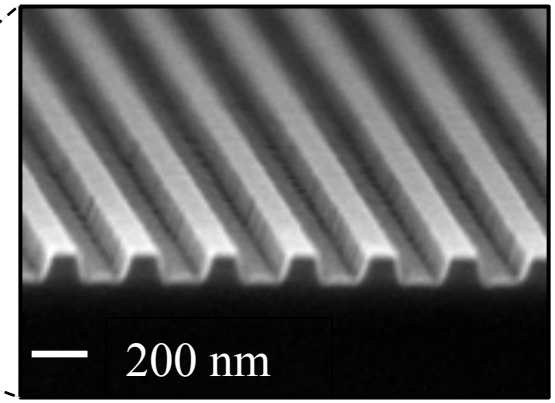
2. Grating Etch

3. Regrowth



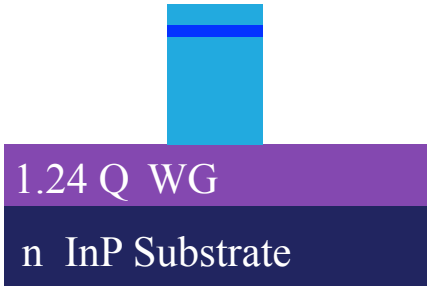


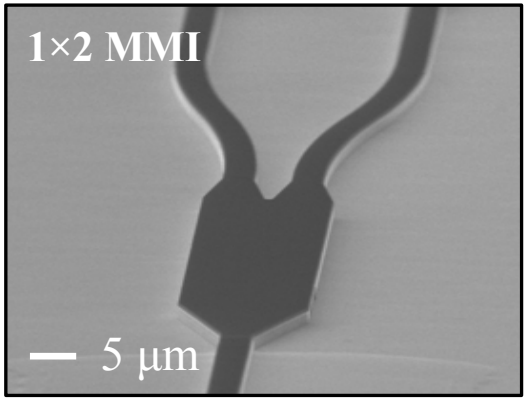


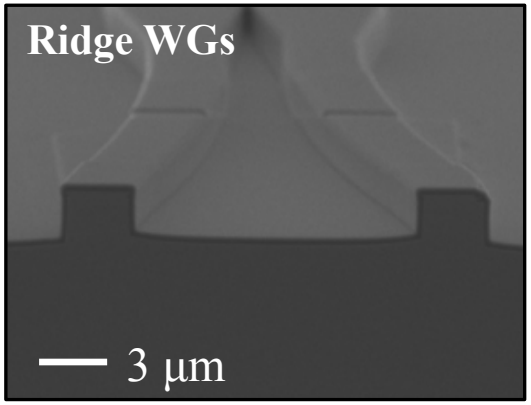


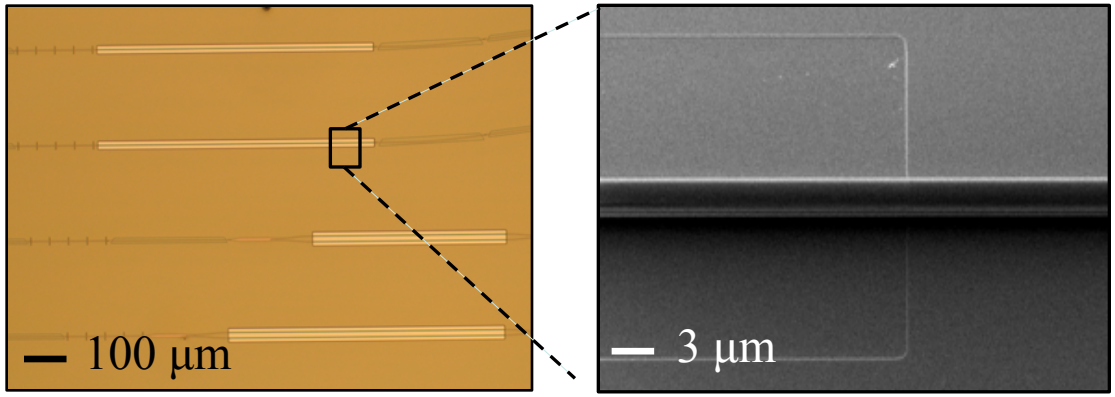
3.1 Fabrication process

4. Ridge etch

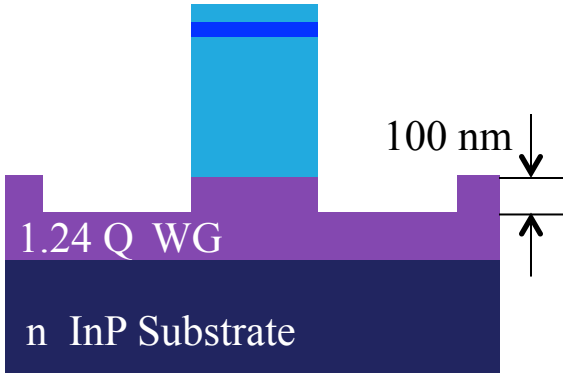




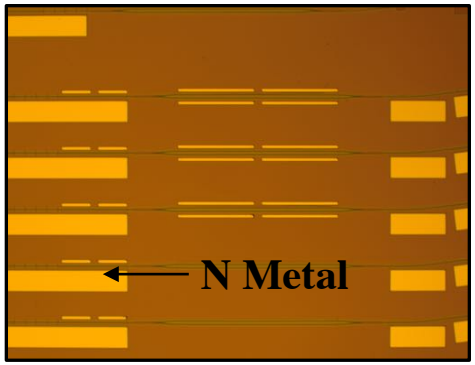


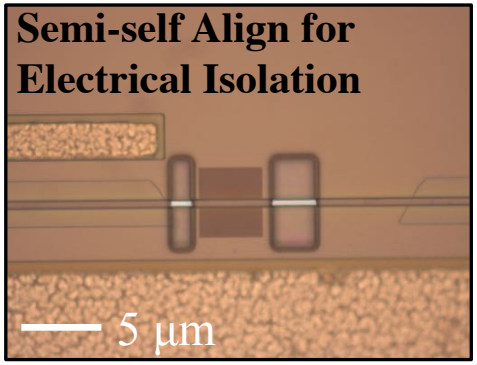


5. Passivation Etch

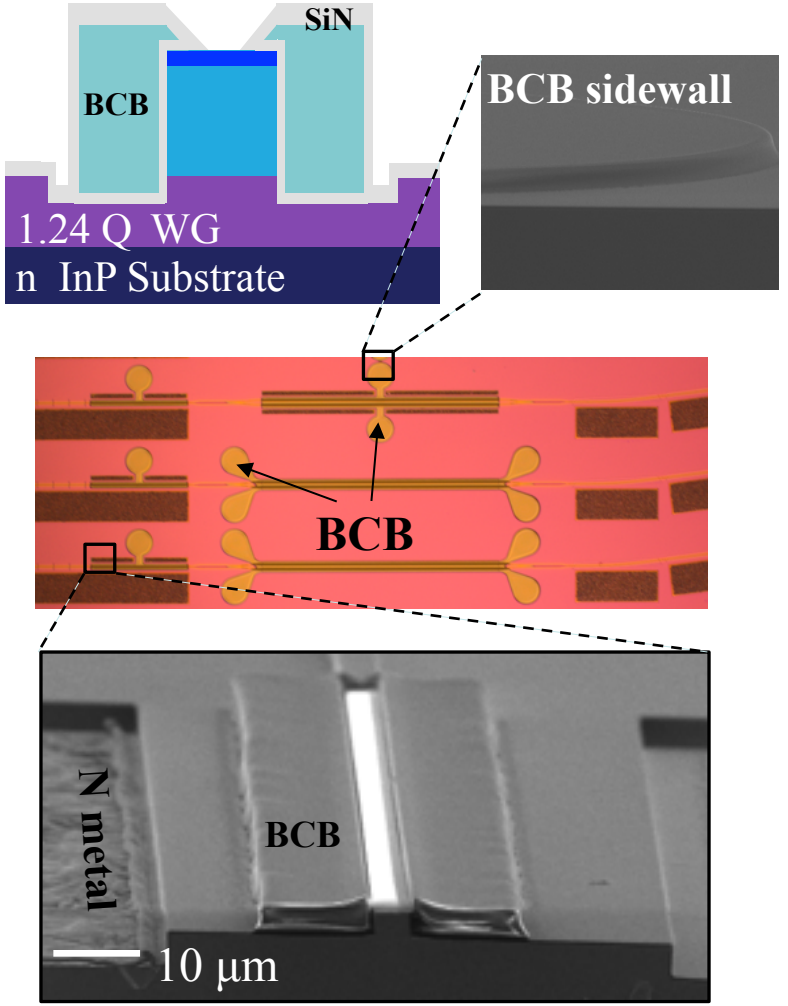


3.1 Fabrication process

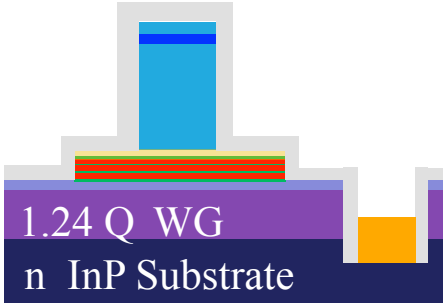




9. BCB Pattern 10. BCB via



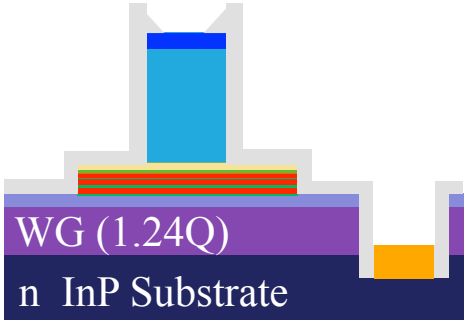
6. N hole etch
7. N metal liftoff



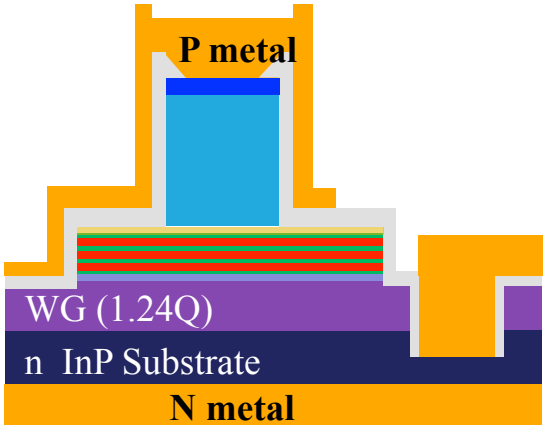
8. Isolation

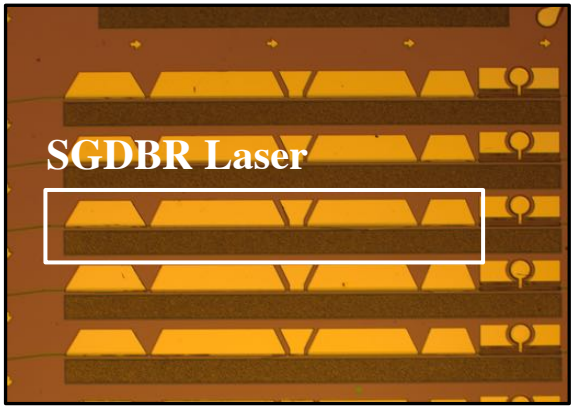
3.1 Fabrication process

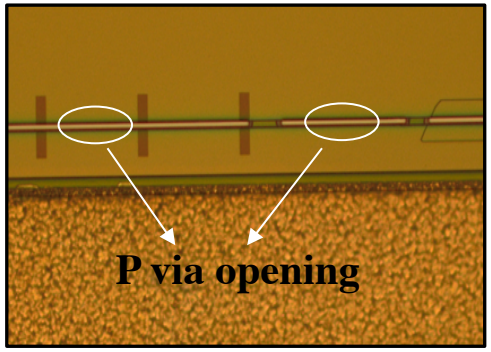
11. P Via

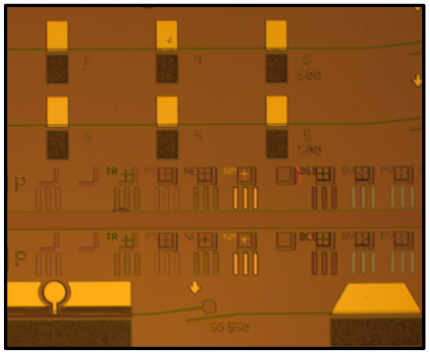


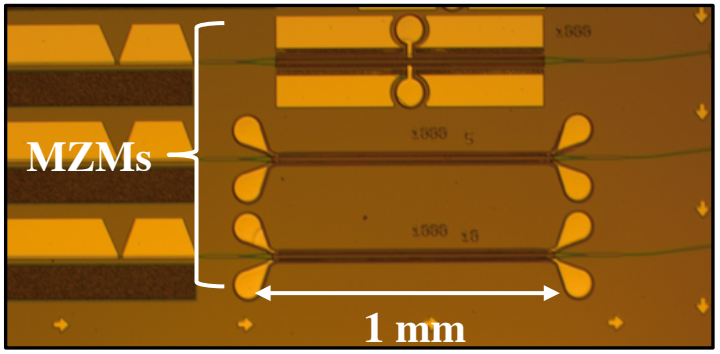
12. P Metal
13. Backside N contact





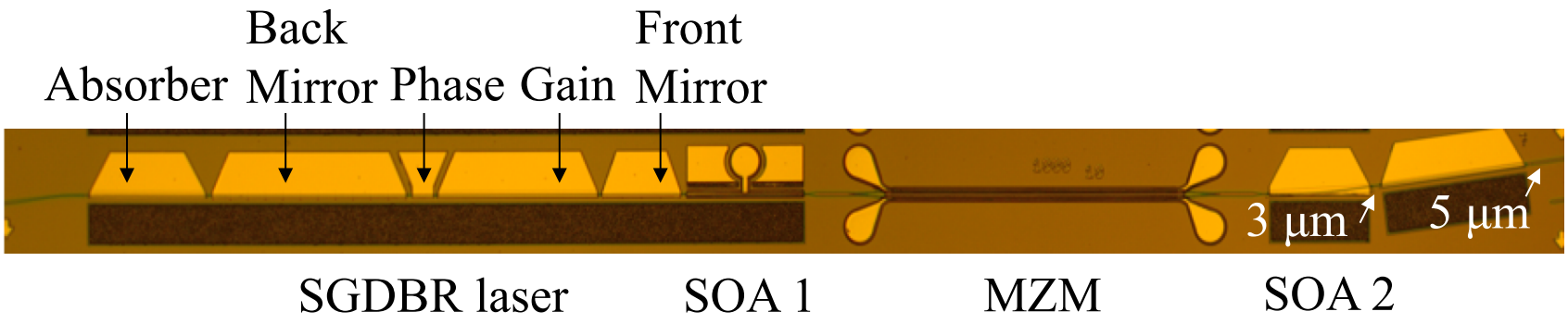


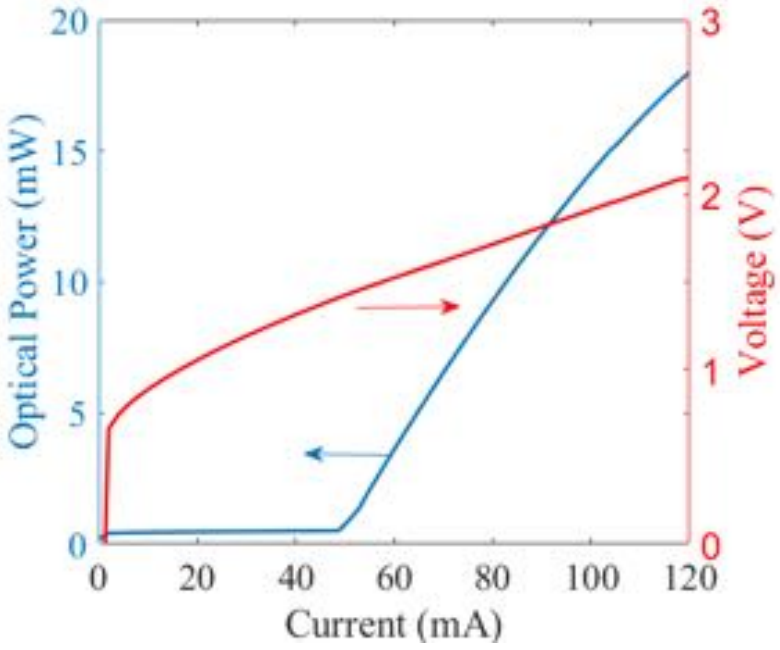


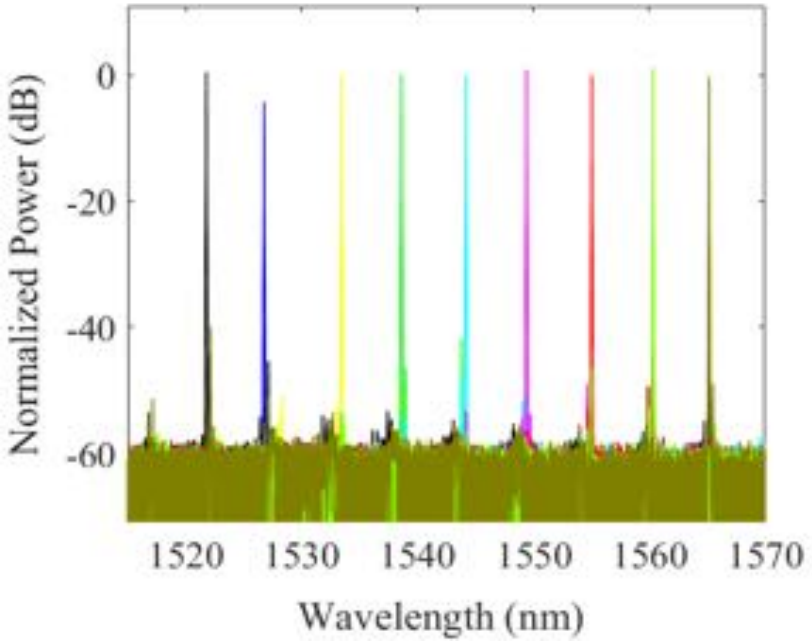


Vernier and test structures

3.2 PIC characterization







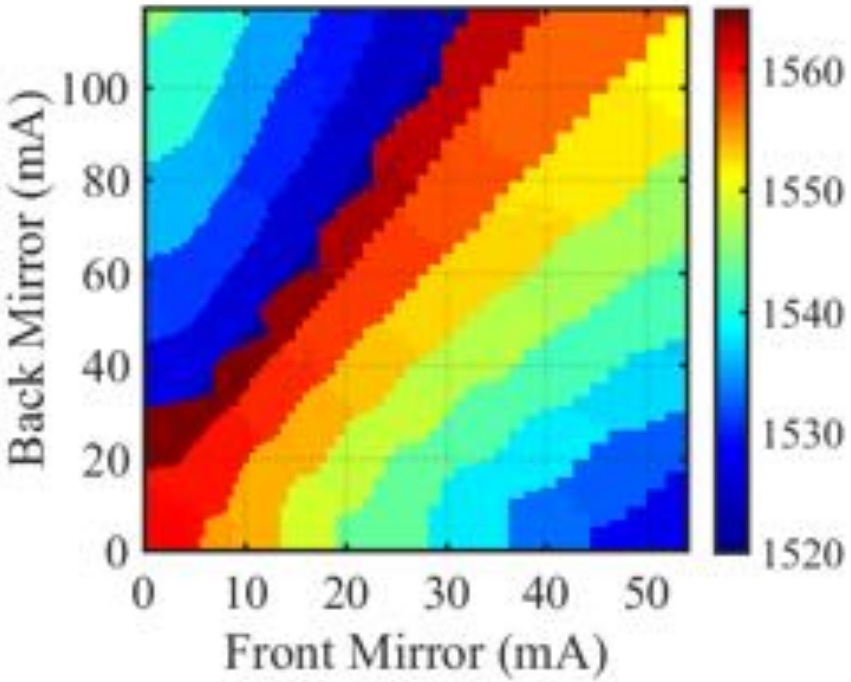
CW Light-Current-Voltage (LIV) characteristic

1521 nm ~ 1565 nm

H. Zhao, et al., IEEE J. Sel. Topic. Quantum. Electron., 24, 6, 2018.

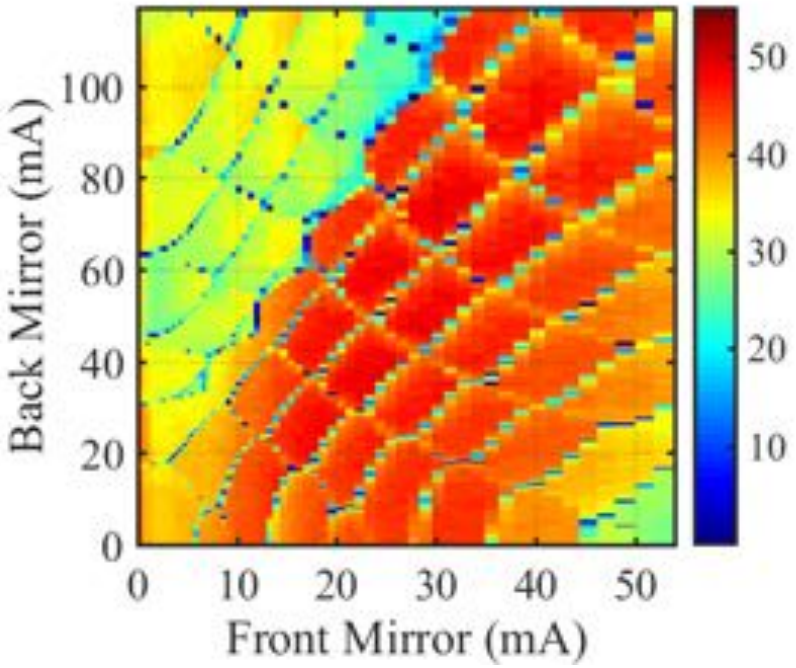
3.2 PIC characterization

Emission Wavelength



44-nm tuning range

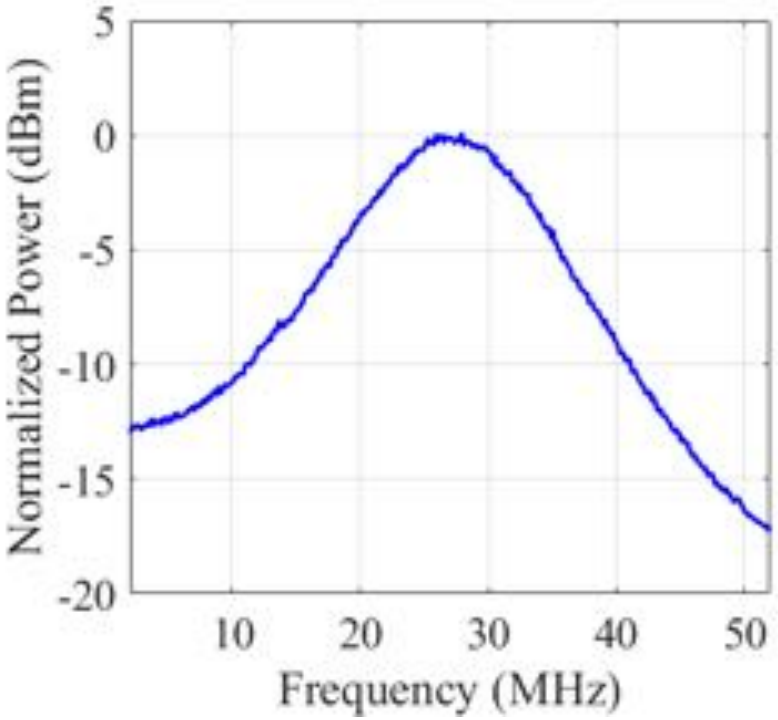
Side Mode Suppression Ratio



> 45 dB SMSR

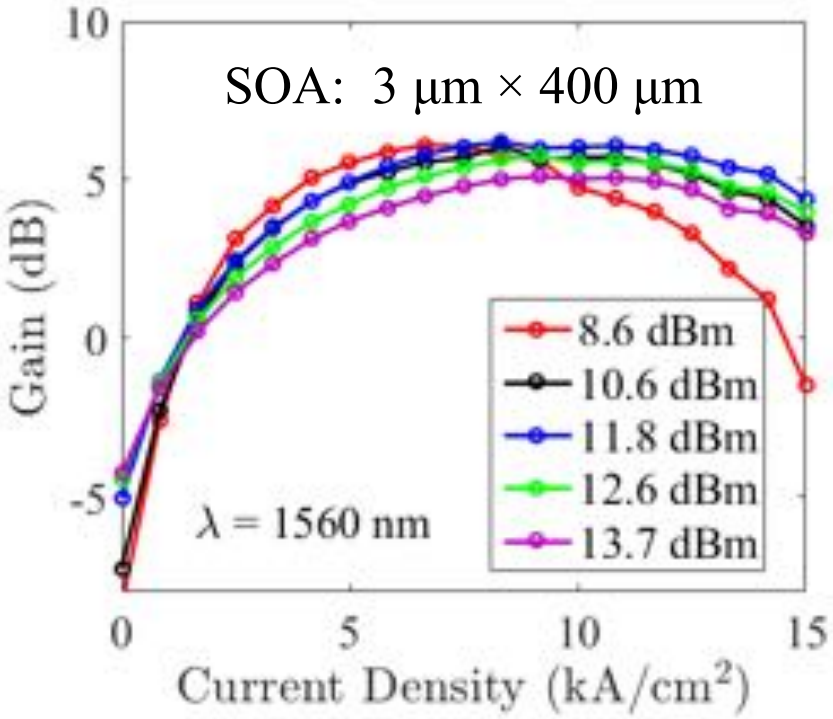
3.2 PIC characterization

Laser linewidth (heterodyne)



6.4-MHz 3-dB linewidth

SOA gain characteristic



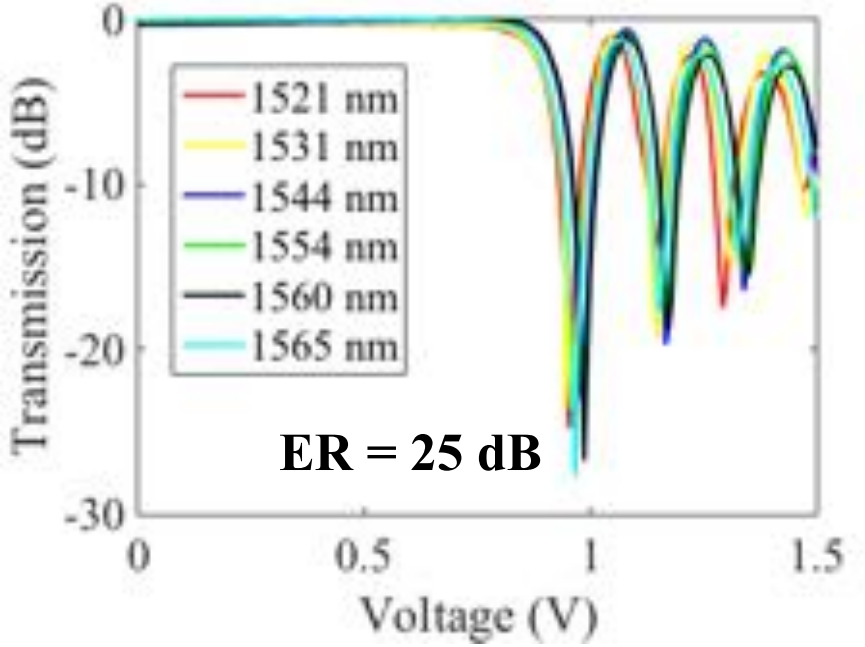
6 dB saturation gain

3.2 PIC characterization

DC Transfer Function of MZM

Forward bias

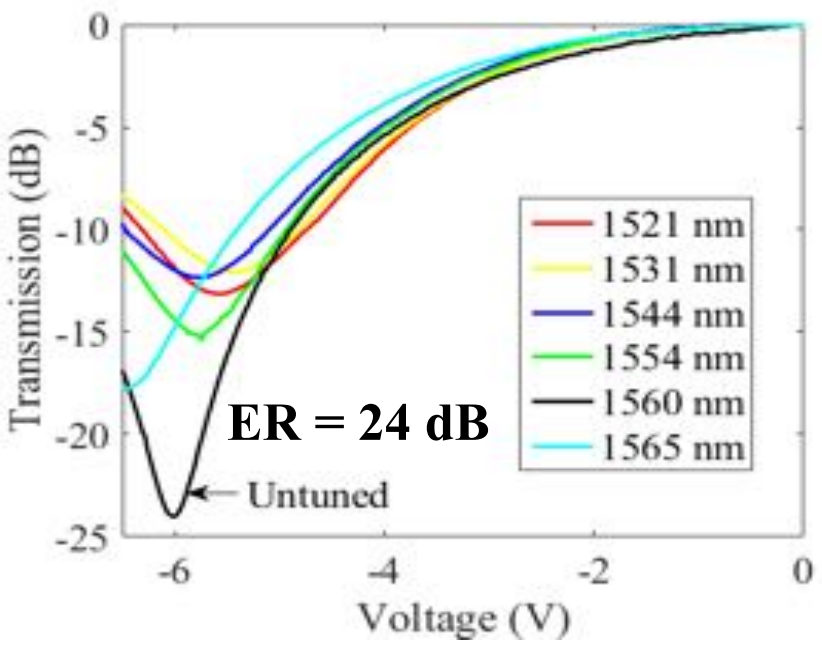
Low data-rate applications (1 Gbps)



$V\pi = 0.2$ V

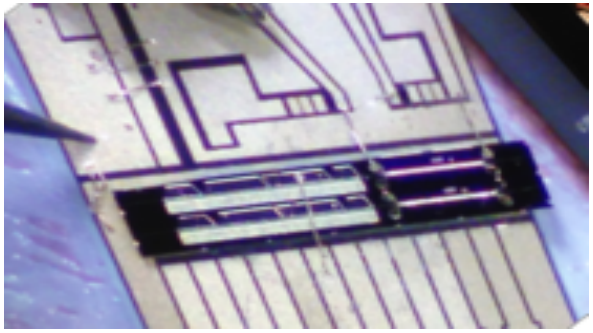
Reverse bias

Higher data rate applications



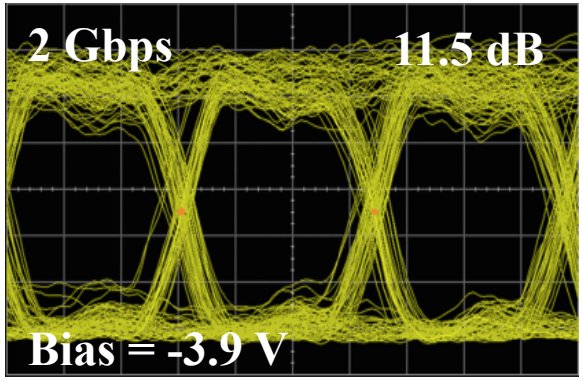
$V\pi = 6$ V

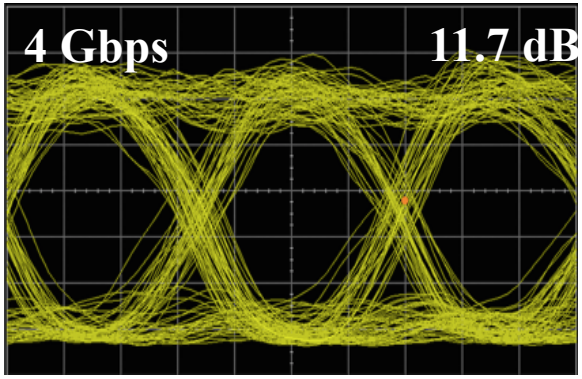
3.2 PIC characterization

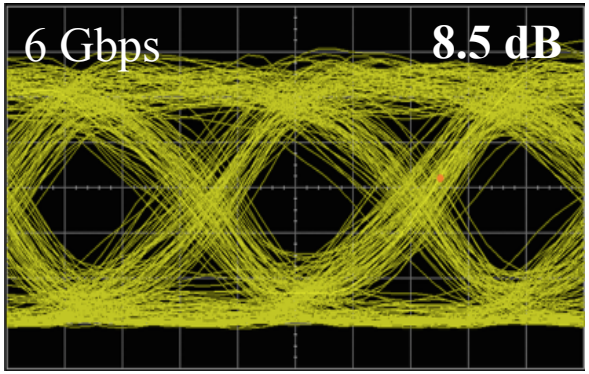


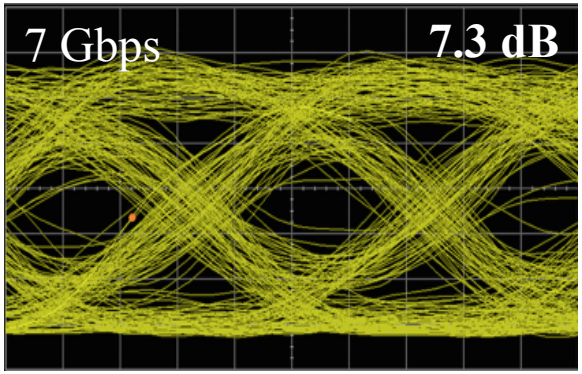
Devices mounted
on ceramic carrier

NRZ OOK Modulation

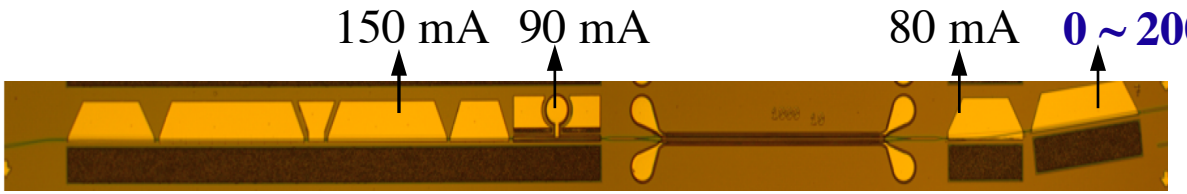


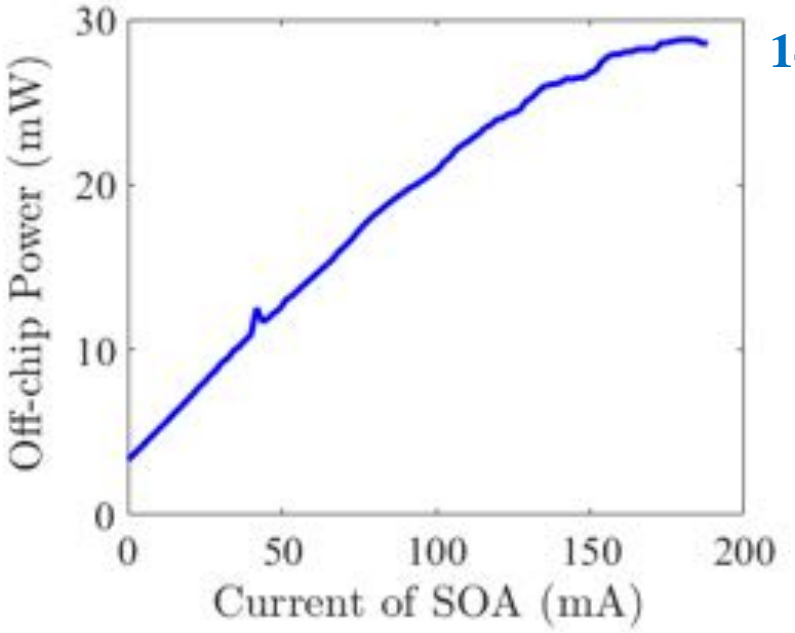






3.2 PIC characterization



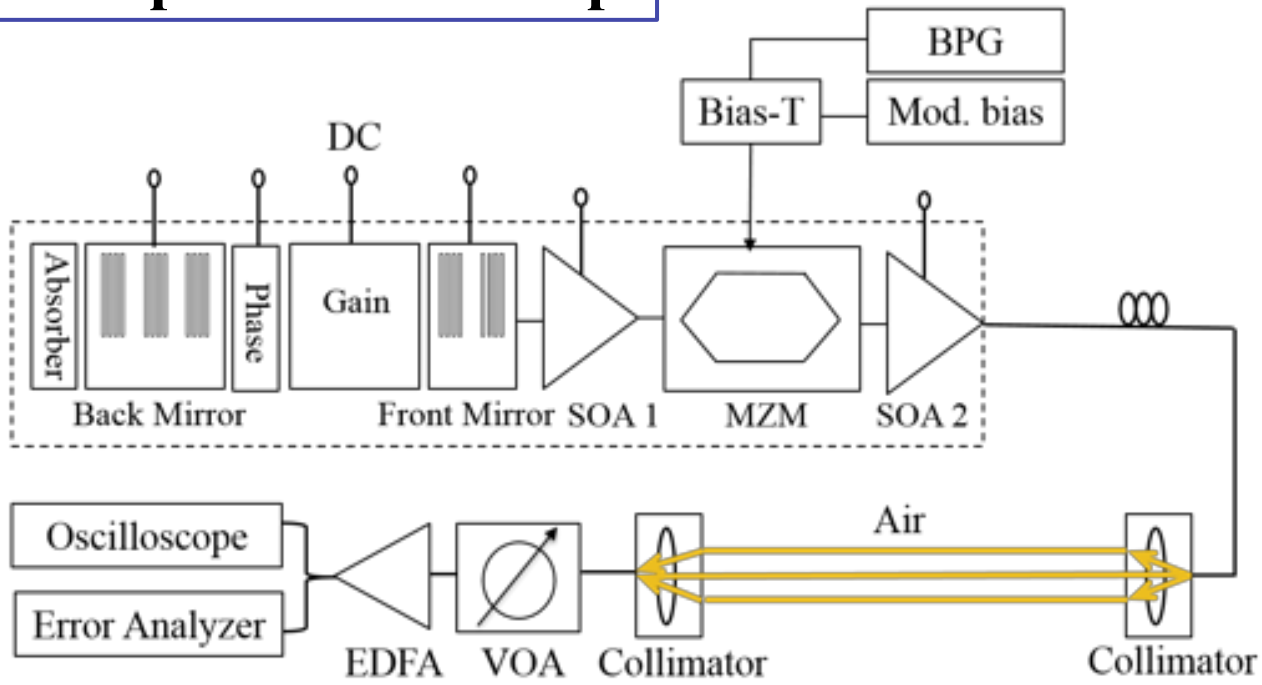


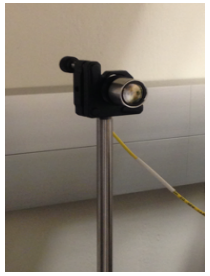
14.5 dBm (28 mW)

Off-chip Optical Power

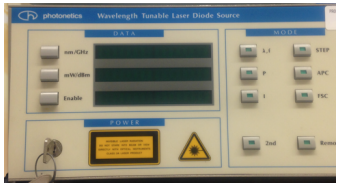
3.3 Free space link

Free Space Optical Link Setup





Collimator



External Cavity Laser

10 GHz Commercial MZM

Reference

3.3 Free space link

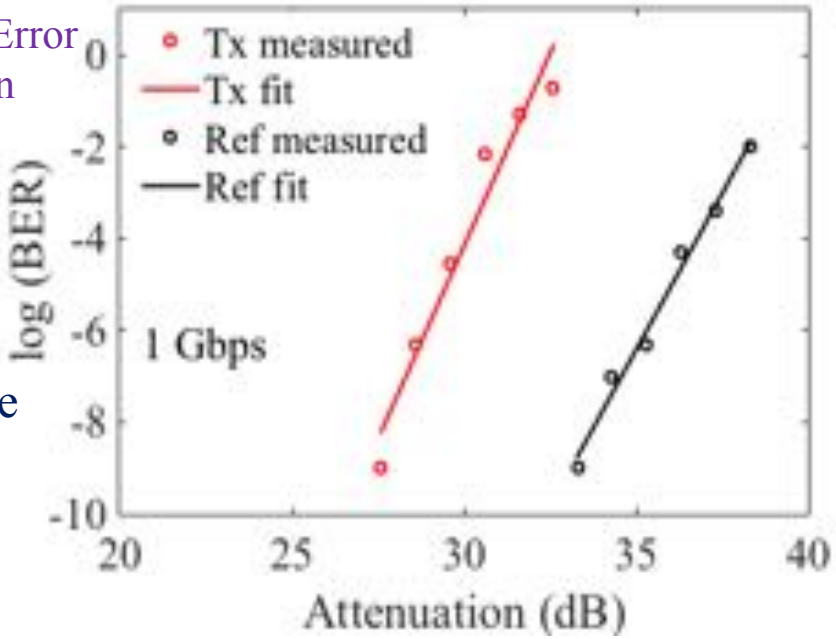
Bit-Error-Rate Measurement

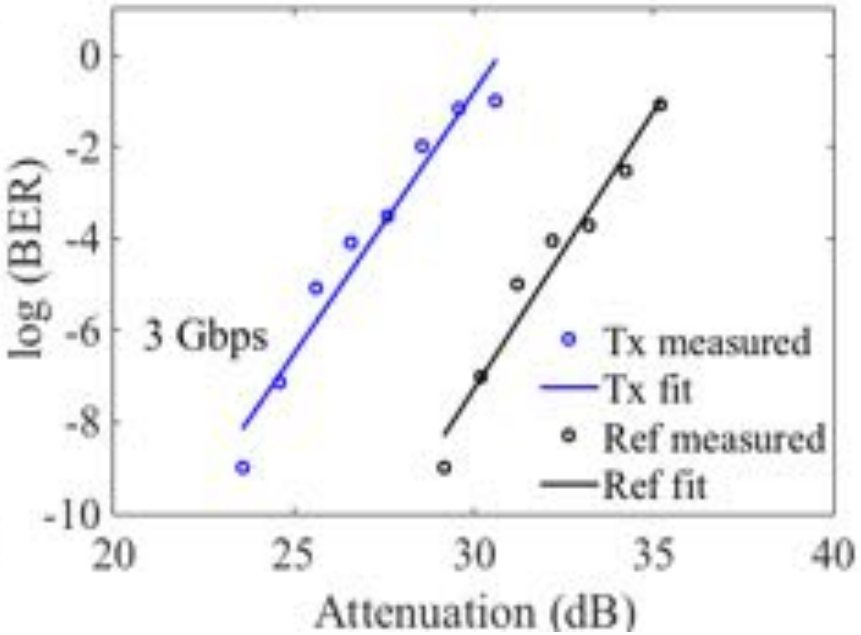
Forward Error Correction

2×10^{-3}

Error free

1×10^{-9}



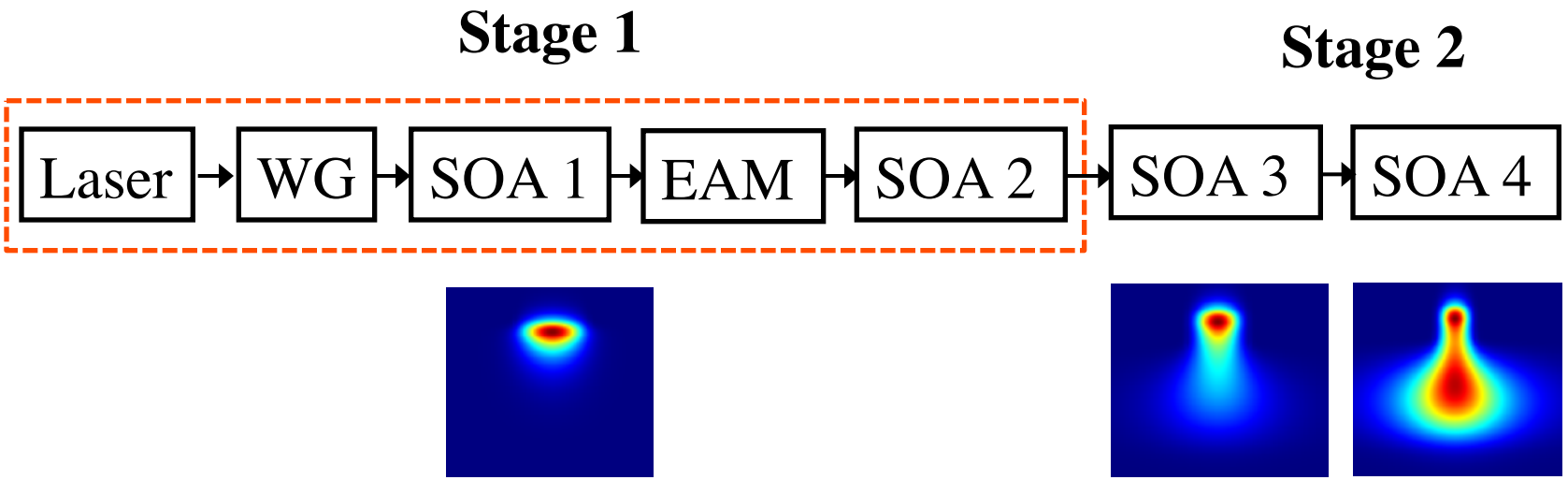


Error free:	**300 m (28 dB)**	**180 m (24 dB)**
FEC:	**400 m (30 dB)**	**300 m (28 dB)**

Outline

- 1. Background
- 2. Epi design
- 3. OQW-based PIC transmitter
- **4. QWI-based PIC transmitter**
  - 4.1 Fabrication process
  - 4.2 PIC transmitter
  - 4.3 High-power SOAs
- 5. Future work

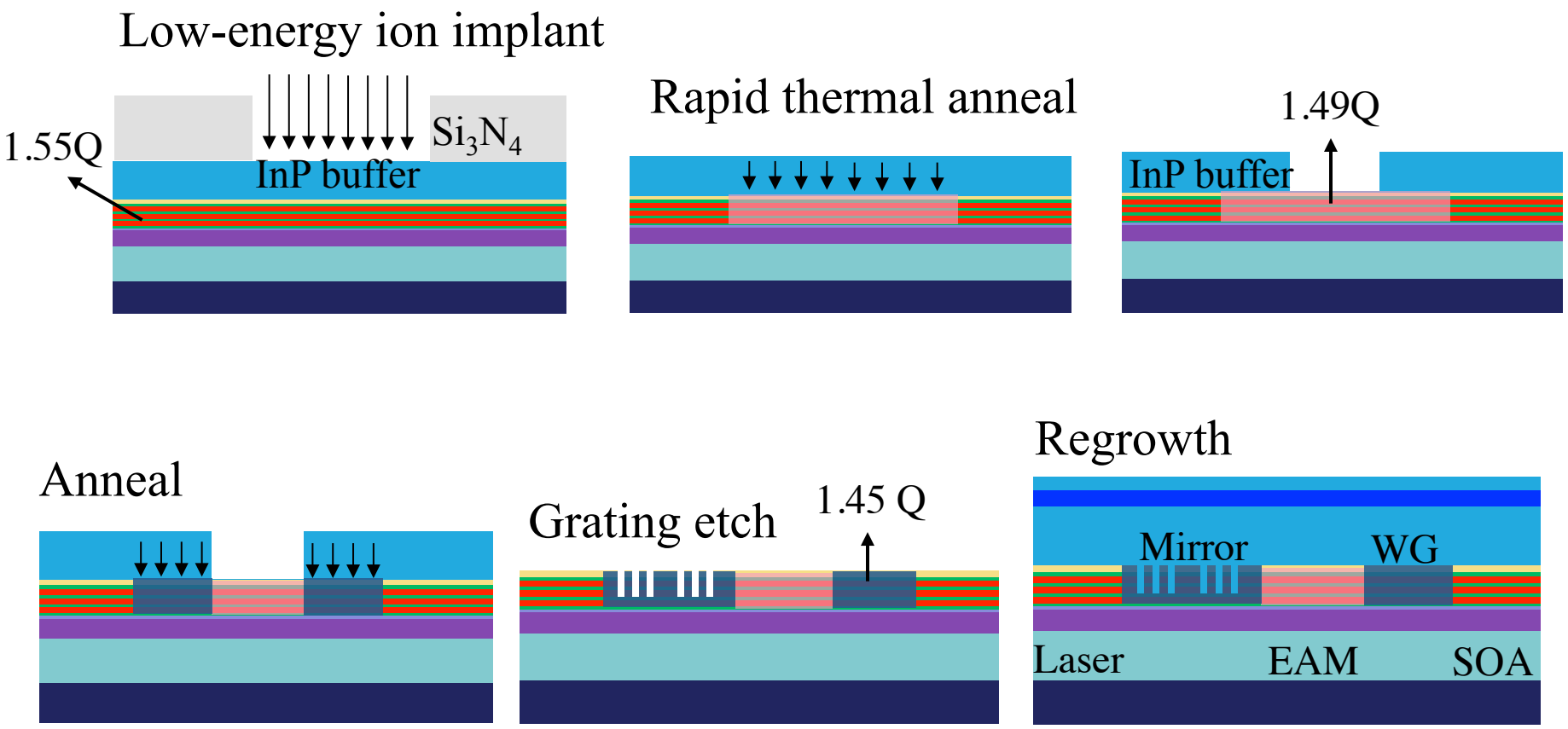
4.1 Fabrication process



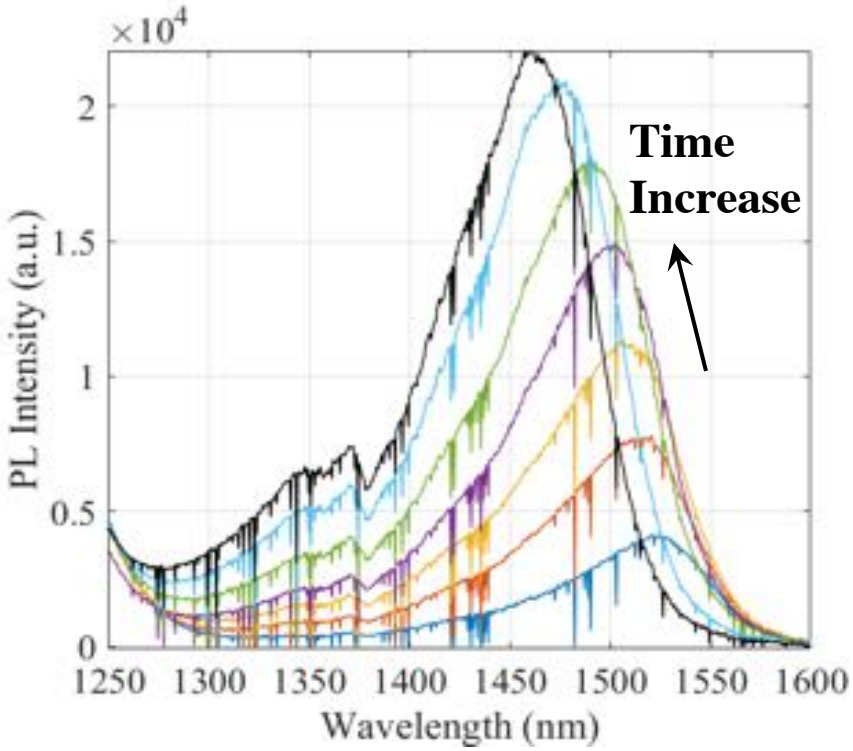
Stage 1: high-confinement WG
SOA 3: transition tapers
SOA 4: low-confinement SOA

4.1 Fabrication process

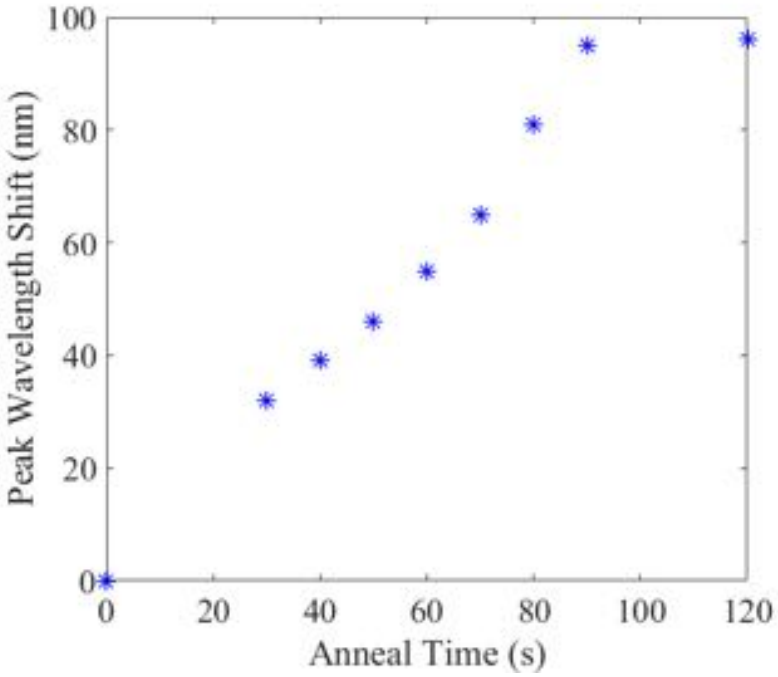
Quantum Well Intermixing



4.1 Fabrication process



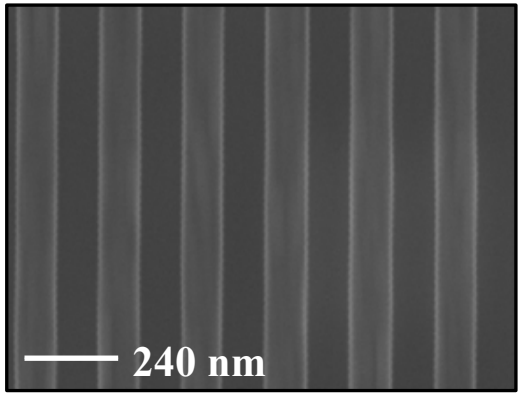
PL vs anneal time



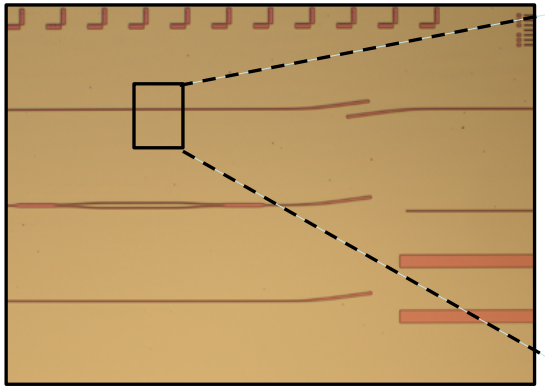
Bandgap shift

4.1 Fabrication process

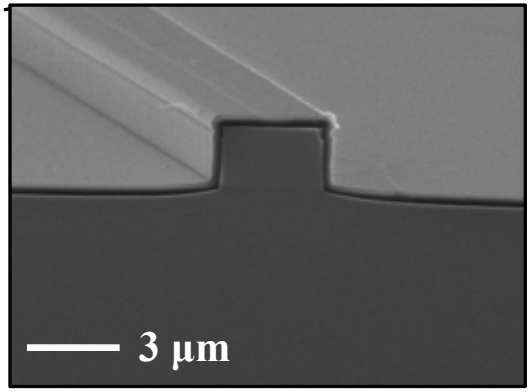
Grating by E-Beam litho

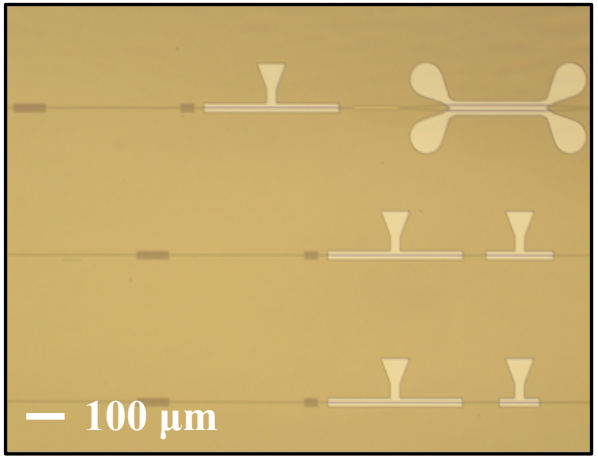


Ridge definition

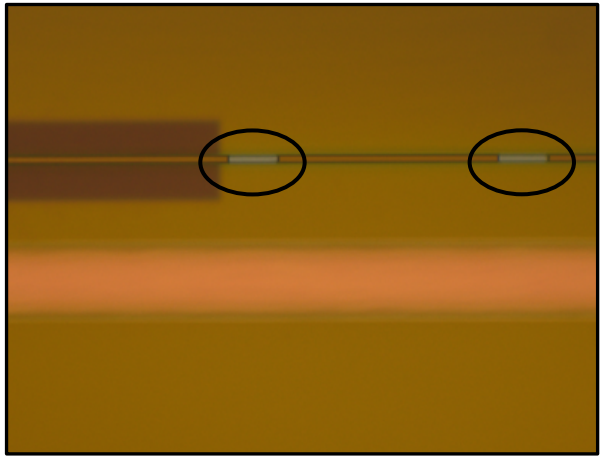


Cross-section of ridge WG



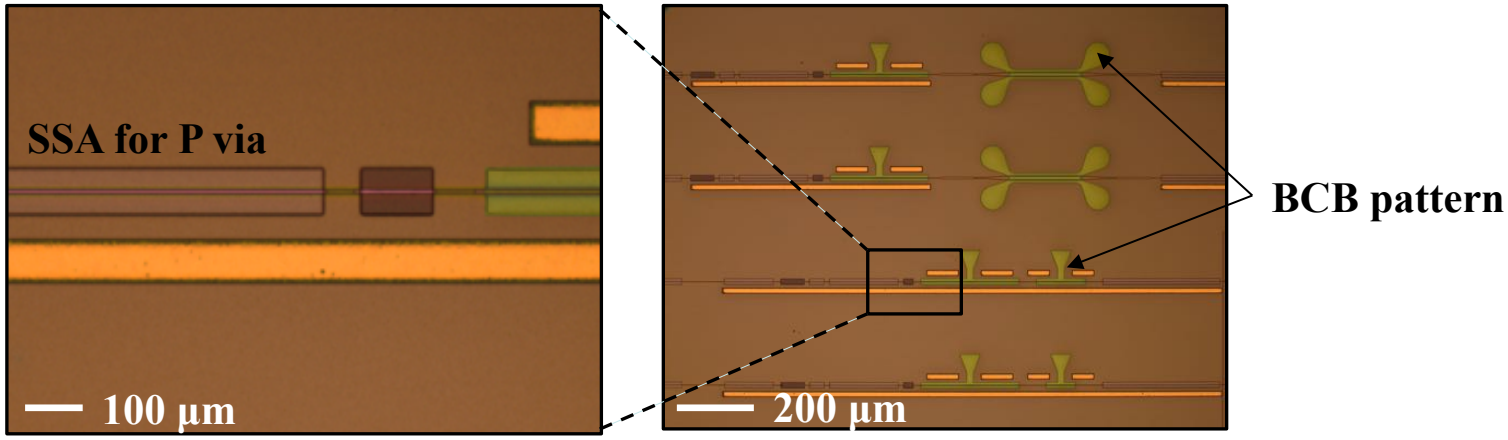


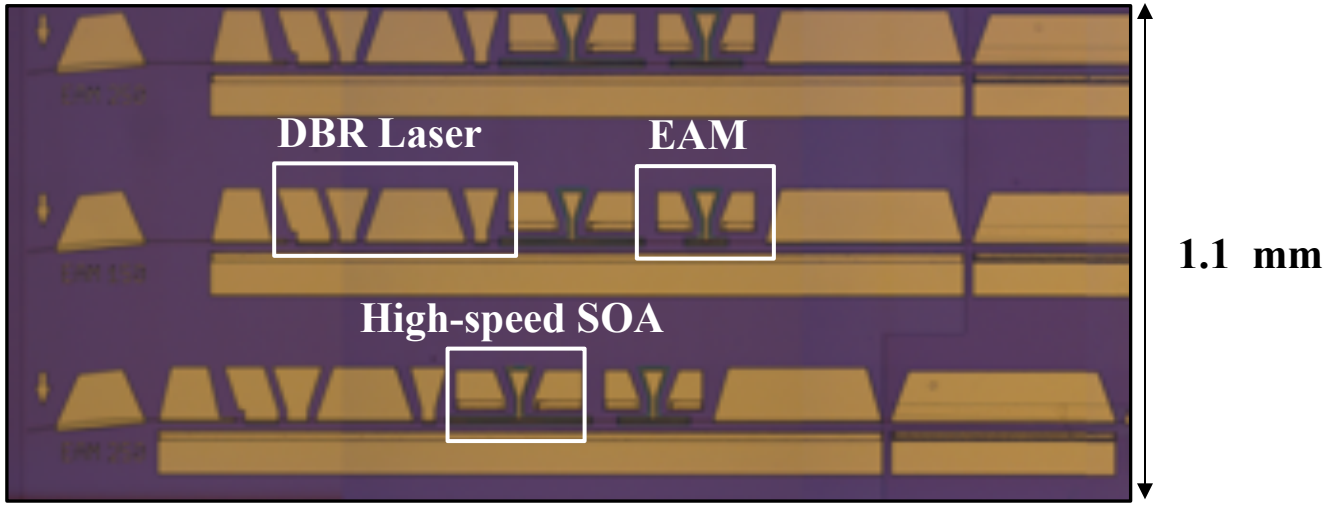
Passivation etch



Isolation

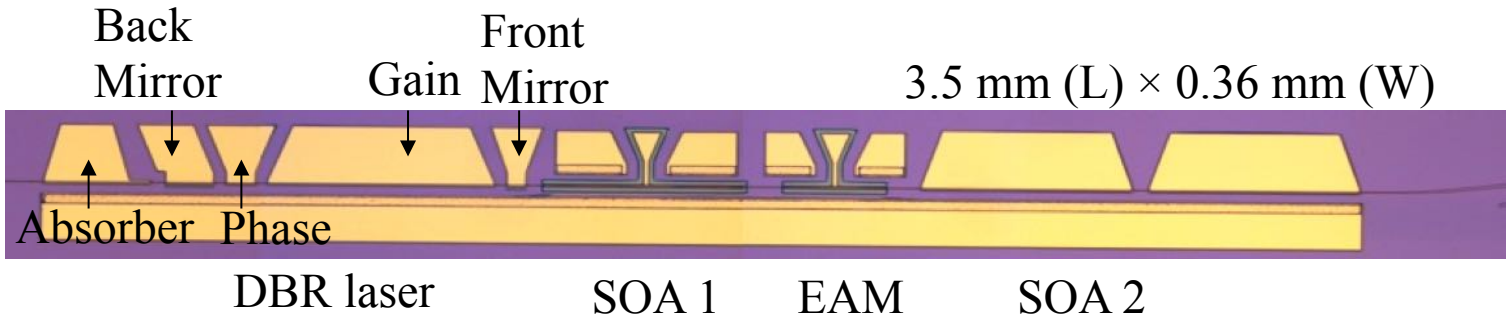
4.1 Fabrication process

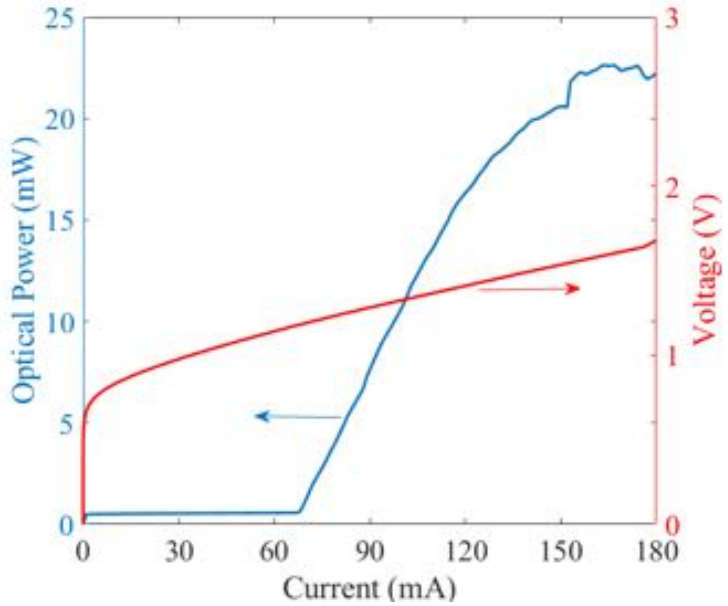




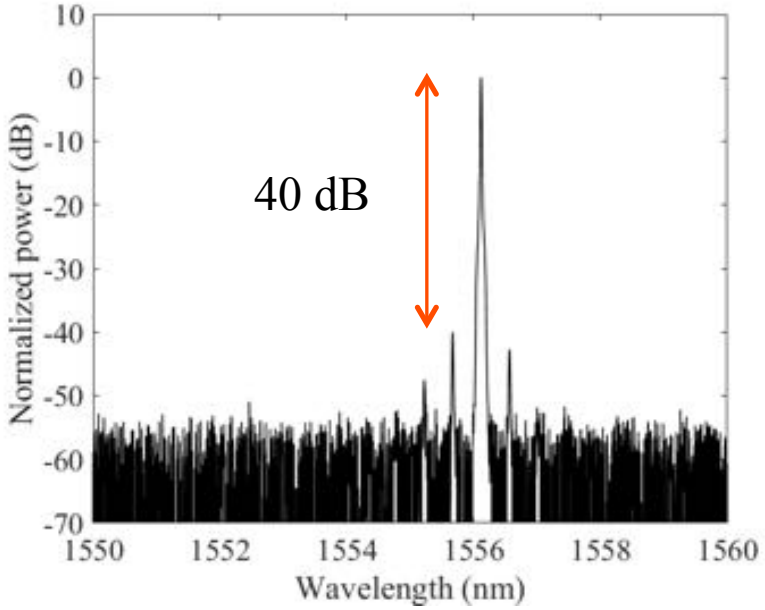
Fabricated PICs

4.2 PIC transmitter





CW LIV characteristic

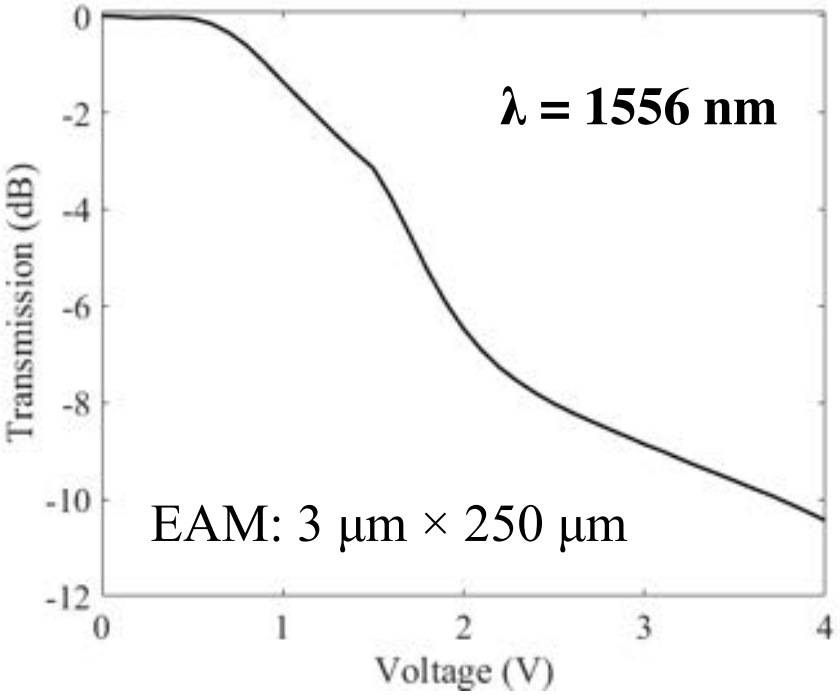


Laser spectrum (Resolution: 0.02 nm)

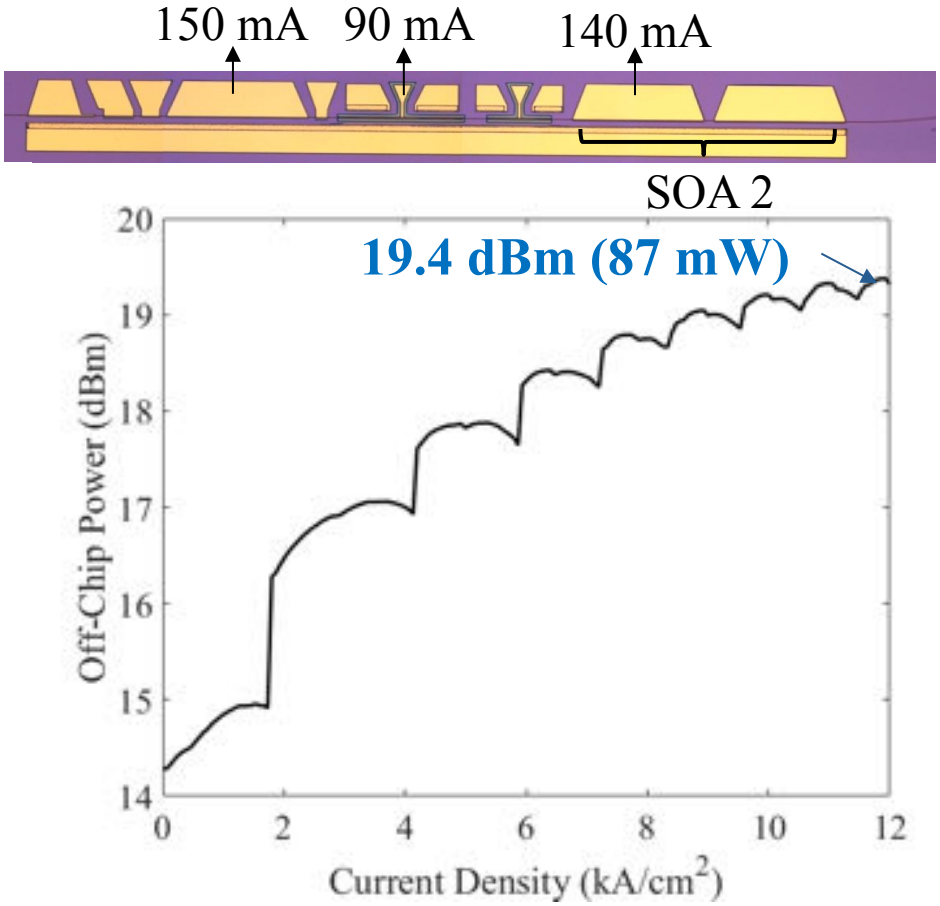
H. Zhao, et al., IEEE J. Sel. Topic. Quantum. Electron., 24, 6, 2019.

4.2 PIC transmitter

Electro-absorption modulator (EAM)



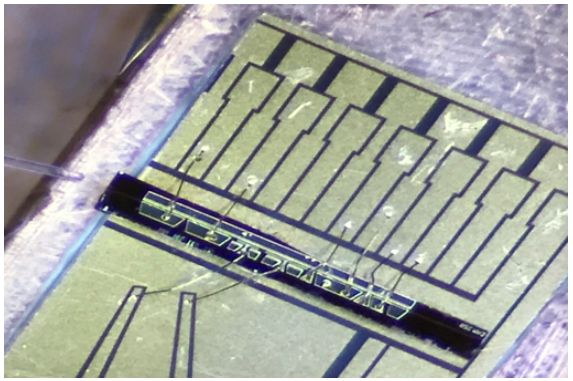
DC Transfer function



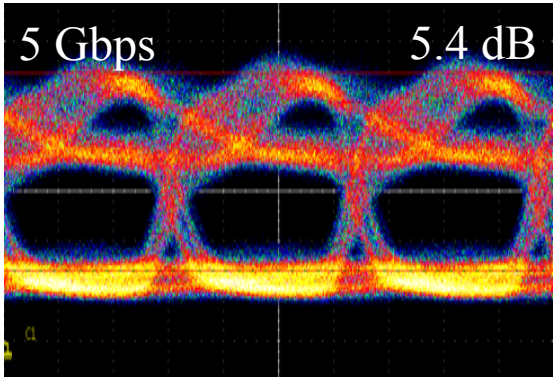
Off-chip optical power

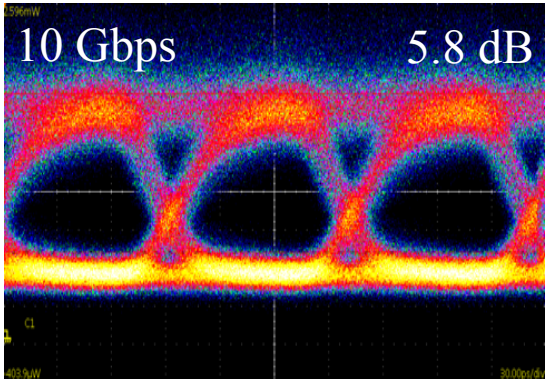
5 dB > OQW Tx

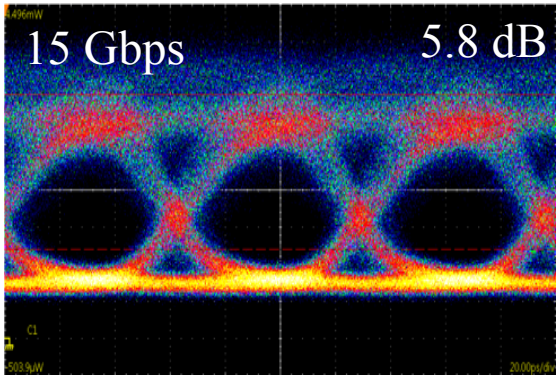
4.2 PIC transmitter

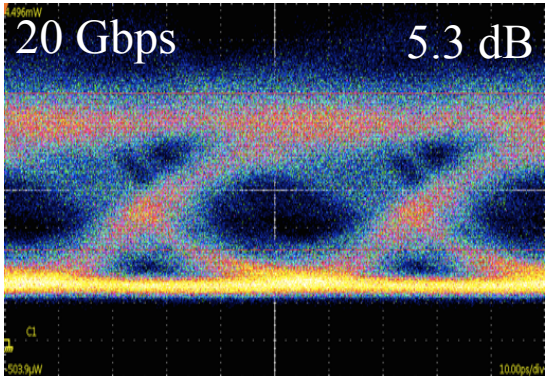


NRZ OOK Modulation

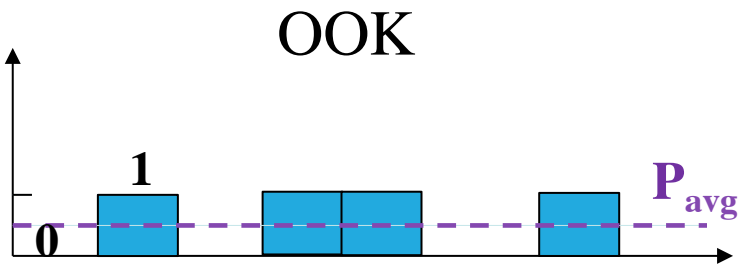




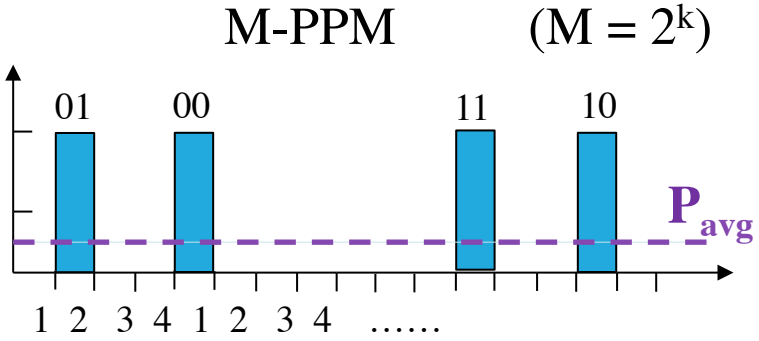




4.2 PIC transmitter

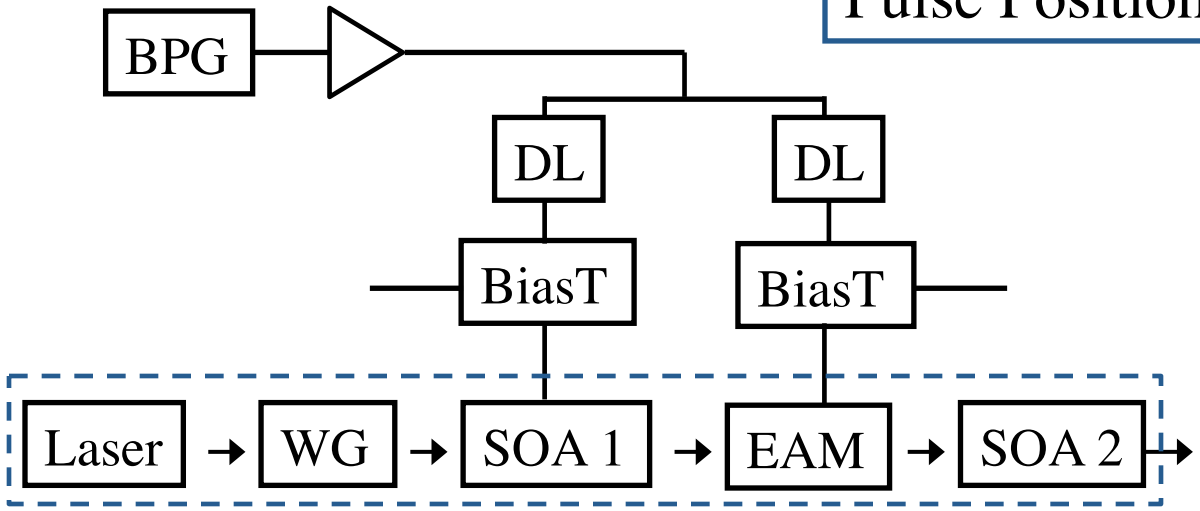


$P_{max} = 2\,P_{avg}$



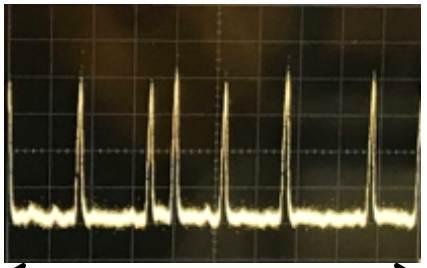
$P_{max} = M\,P_{avg}$ (M=4, k = 2)

Pulse Position Modulation (PPM)



Schematic of PPM test setup

16-PPM

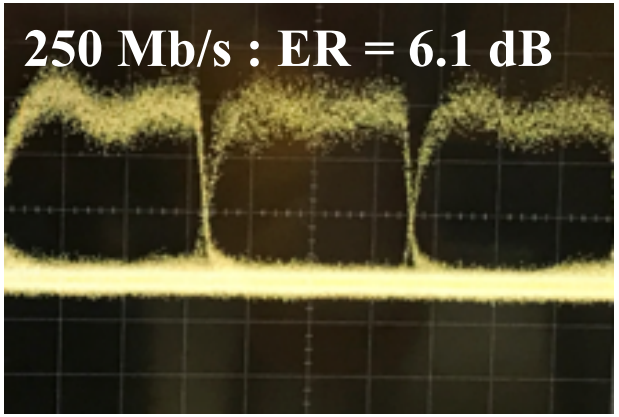


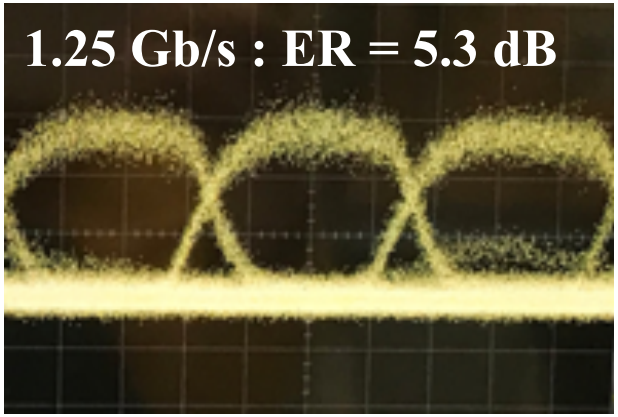
1 ns

4.2 PIC transmitter

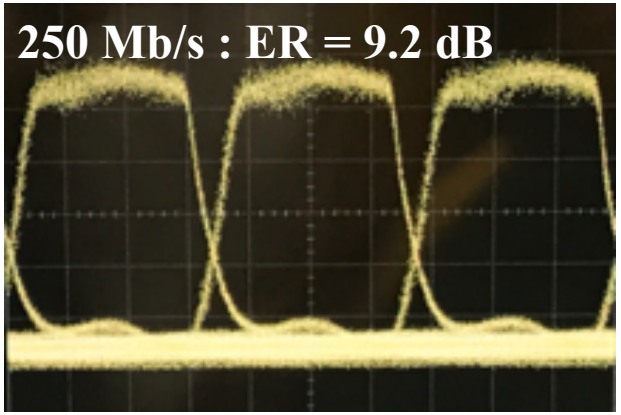
16-PPM

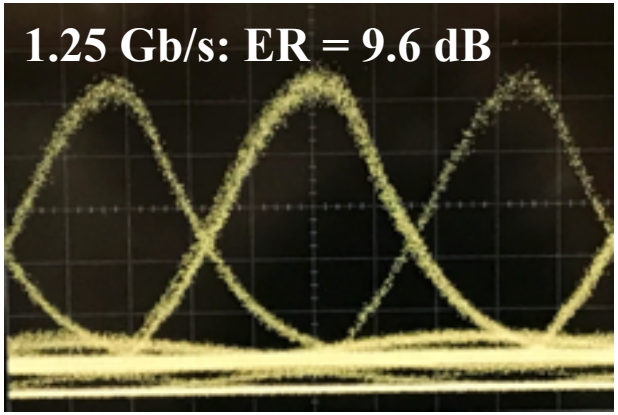
EAM modulated





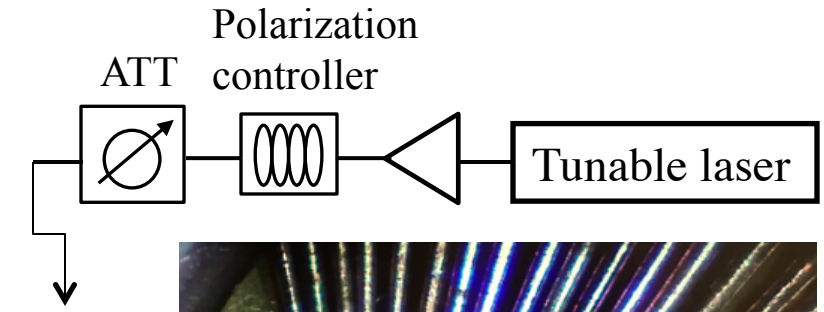
Both EAM and SOA1 modulated

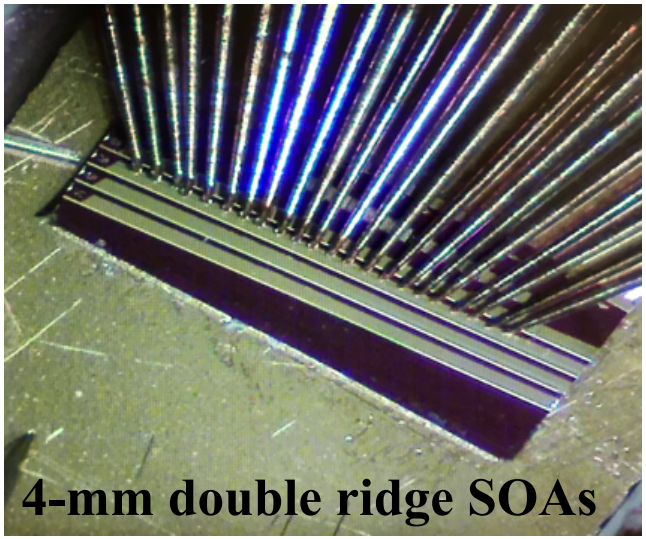


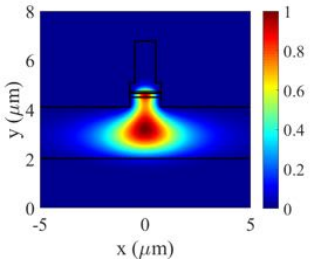


Low data rate applications

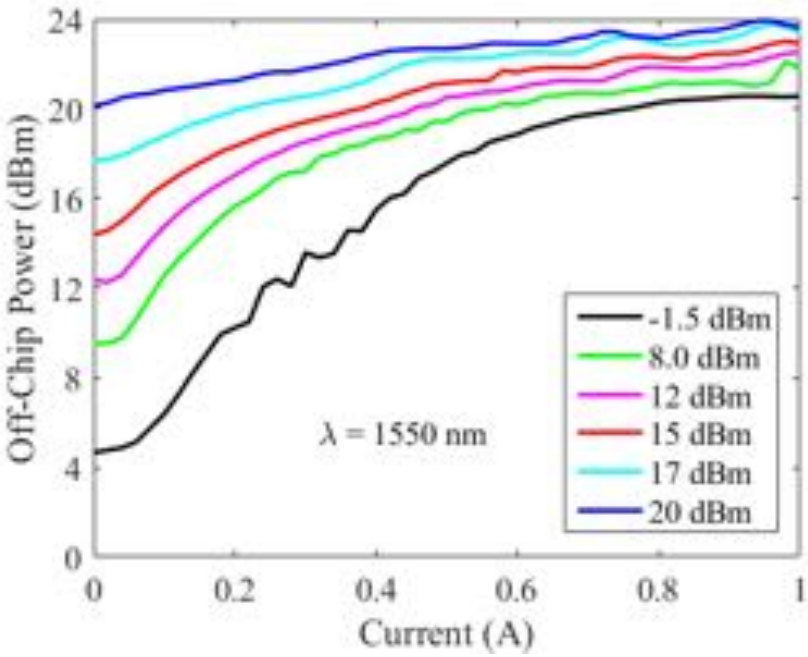
4.3 High power SOA







Off-chip optical power

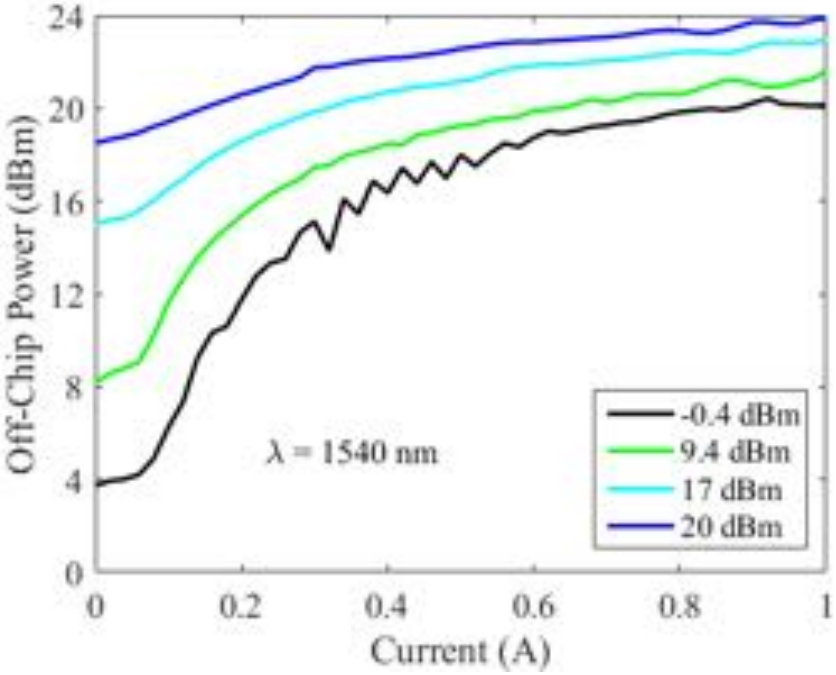


Max optical power: 24 dBm (250 mW)

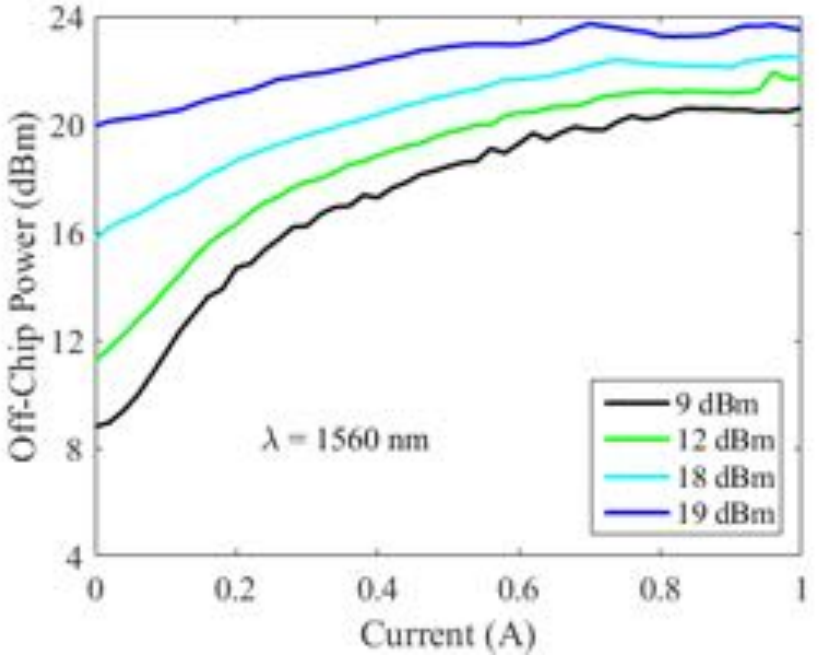
H. Zhao, et al., *Device Research Conference (DRC)*, 2019.

4.3 High power SOA

Broadband Operation



Max optical power: 23.9 dBm



Max optical power: 23.7 dBm

4.4 High-power SOA

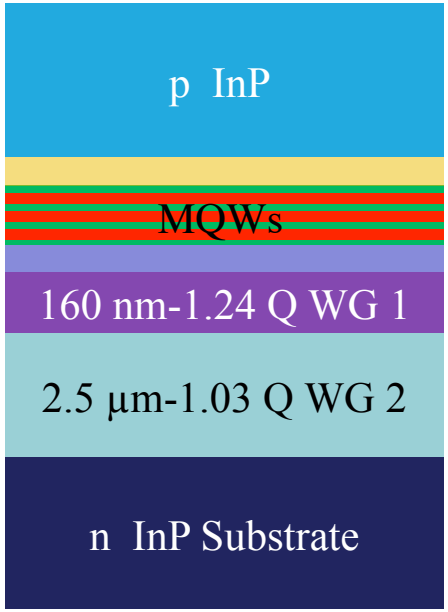
Tx	Laser-MO	SOA	Data Rate	Link Length*
OQW	10 mW	28 mW	7 Gbps	~ 300 m
QWI- Stage 1	10 mW	87 mW	20 Gbps	~ 500 m
QWI- Stage 2	10 mW	250 mW	20 Gbps	~ 900 m

* Link length without HPA.

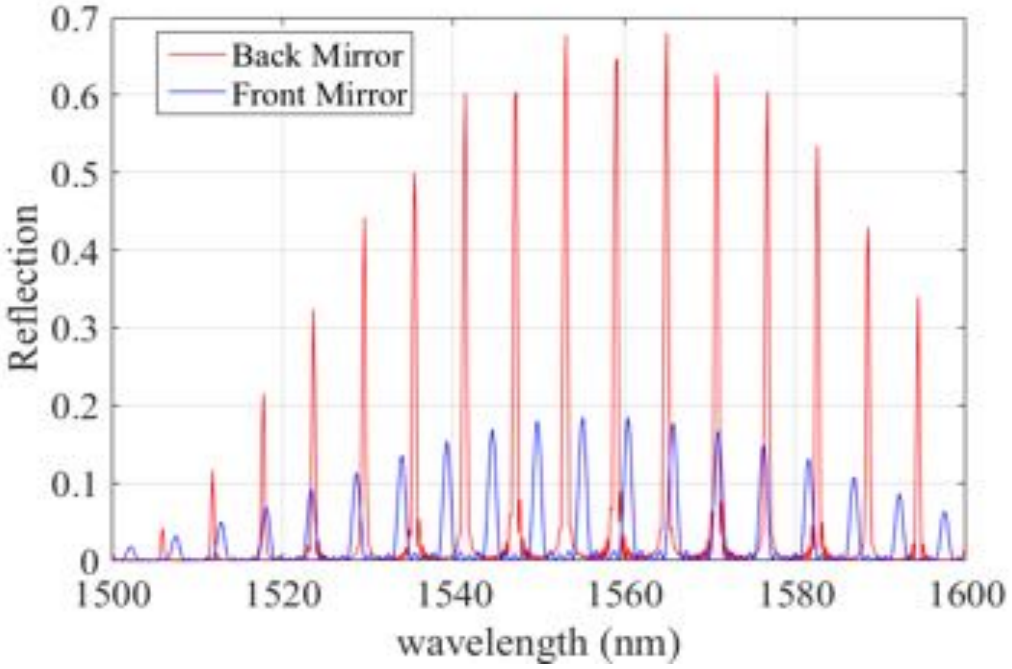
Outline

- 1. Background
- 2. Epi design
- 3. OQW-based PIC transmitter
- 4. QWI-based PIC transmitter
- **5. Future work**

5. Future work



SGDBR laser

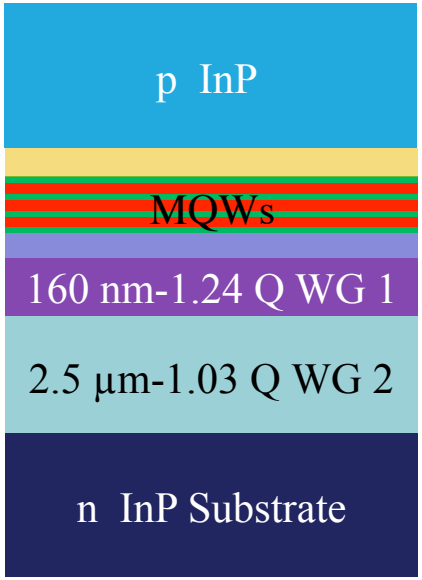


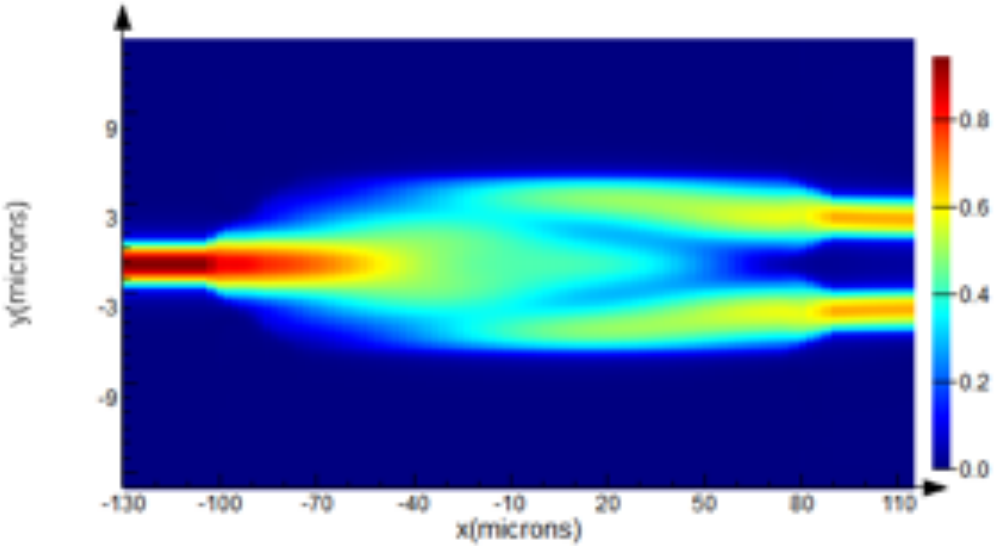
Front mirror: W = ~~4 μm~~ 5 μm, P =68.5 μm, M = 5

Back mirror: W= 6 μm, P=61.5 μm, M = ~~12~~ 15

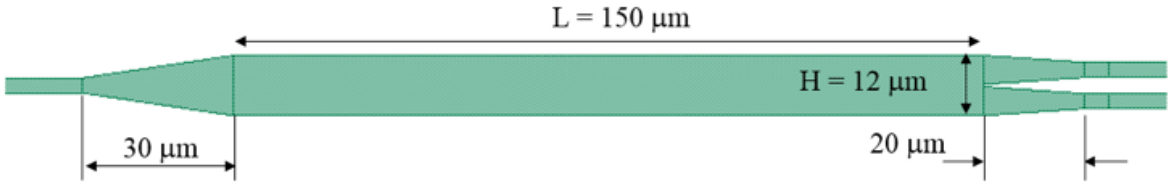
5. Future work

Mach-Zenhder Modulator



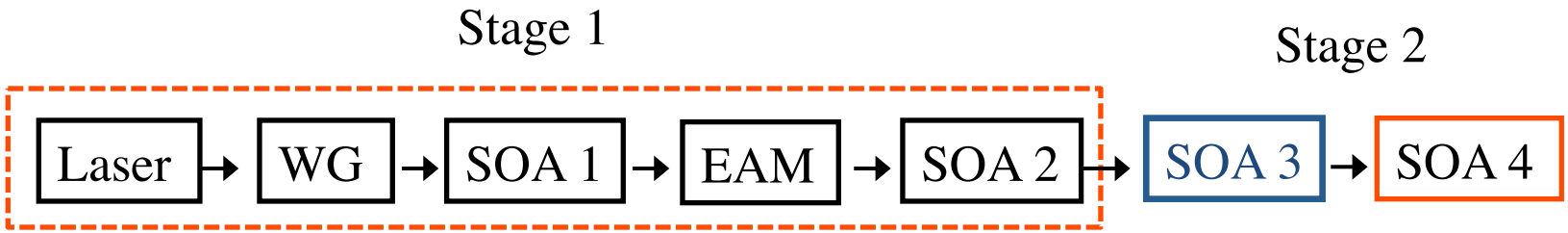


EME simulation of a 1 × 2 coupler

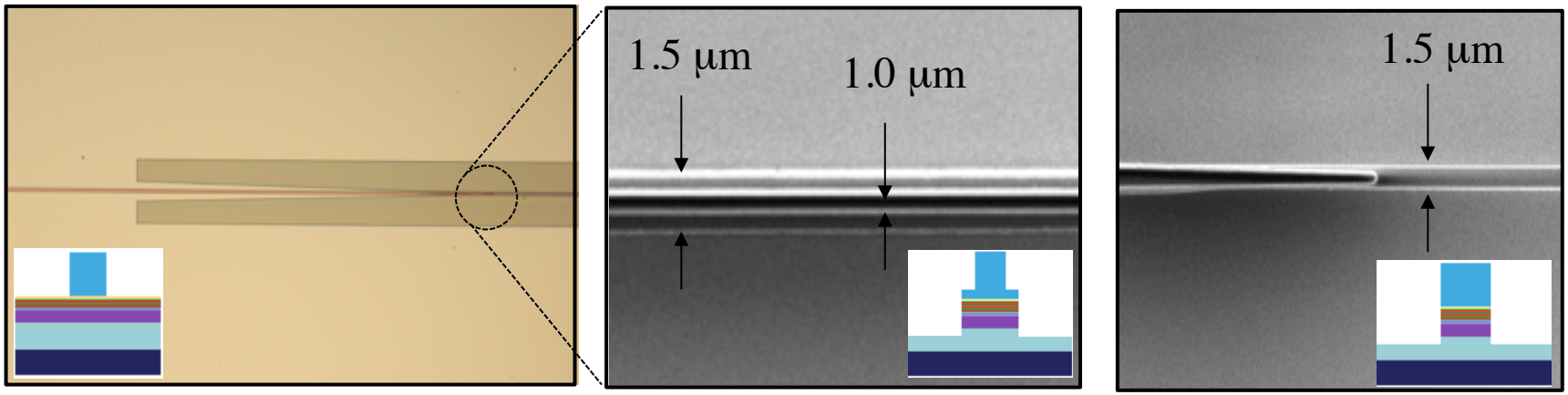


1 × 2 coupler

5. Future work



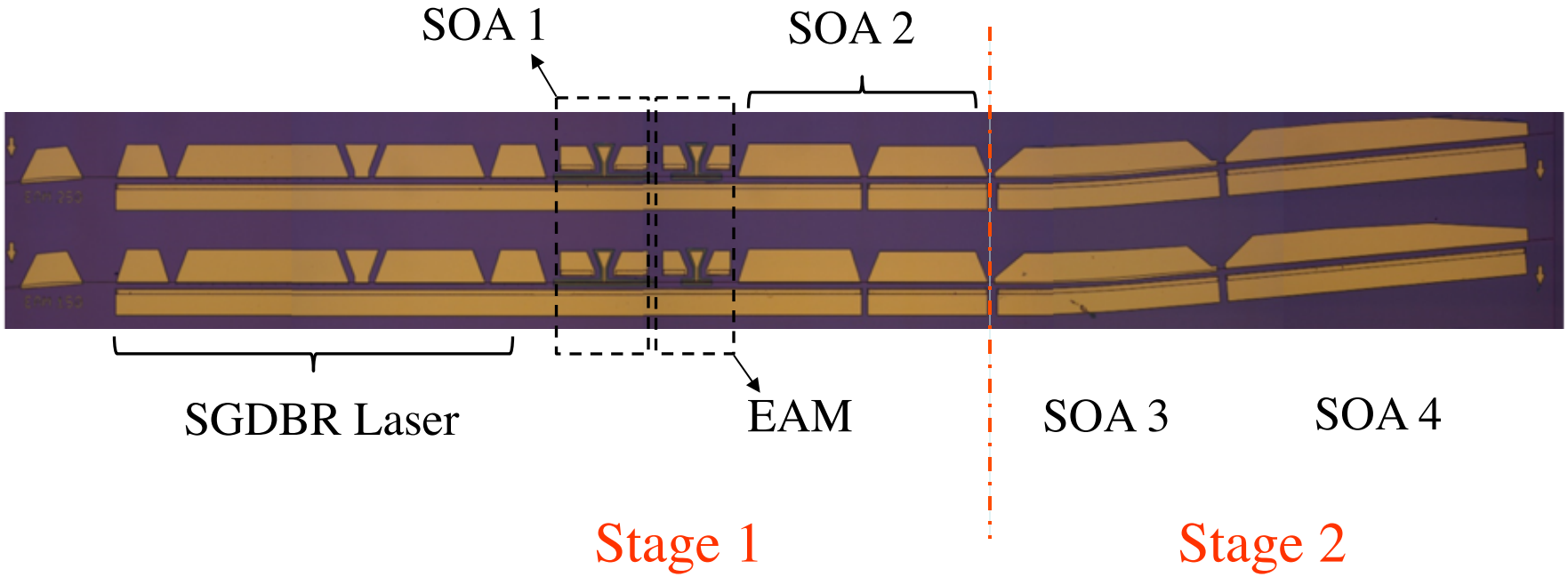
Transition section



Full integration of Stage 1 Tx with advance high-power SOAs

5. Future work

8 mm (L) × 0.36 mm (W)



PIC Txs integrated with advanced SOAs

Summary

- Gen 1 OQW Tx

SGDBR laser SOA MZM output SOA

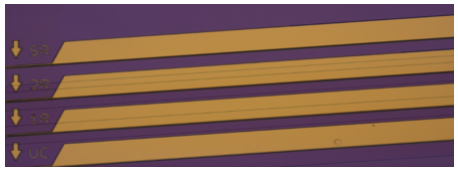
14.5 dBm

- Gen 2 QWI Tx

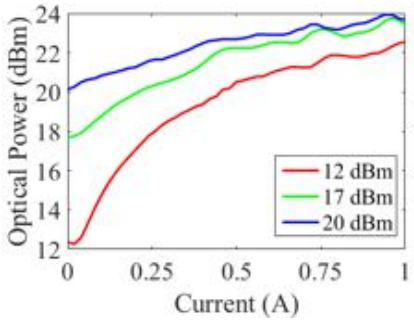
DBR laser SOA EAM output SOA

19.4 dBm

- Gen 2 low- Γ SOA



24 dBm



- Demonstrated a high-power PIC platform for low CSWaP free space transceivers for small satellite applications
  - PIC transmitter with 20-Gbps modulator and high-power booster SOA;
  - Advanced SOA up to 24 dBm output power.

Acknowledgement

Thanks