硅基量子点光频梳激光器

王 霆

中国科学院物理研究所

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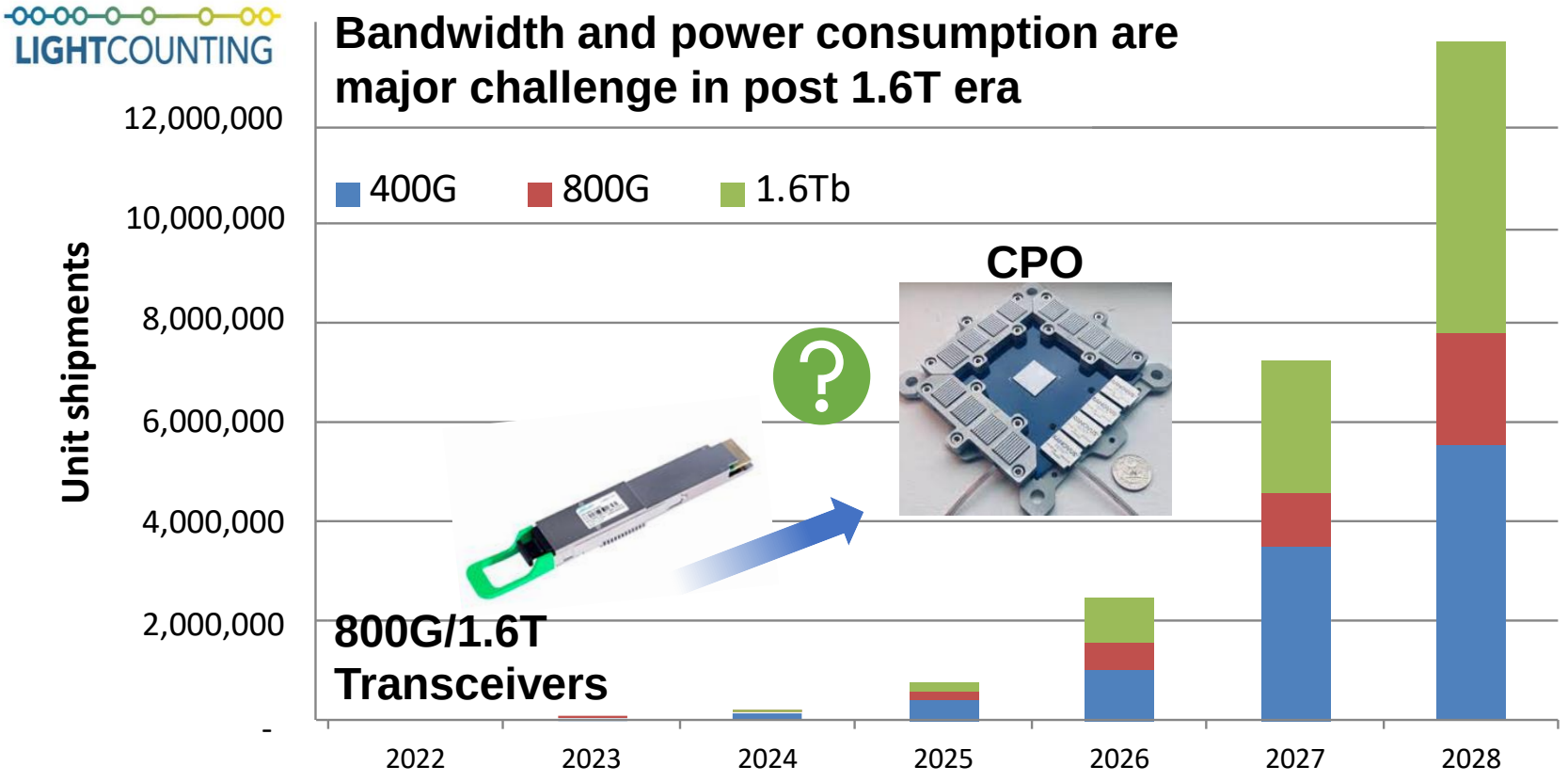
Outline

I. Multiwavelength lasers for CPO/optical chiplet
II. InAs QDs comb lasers
III. High order QDs comb lasers for WDM systems
IV. Monolithically integrated QD comb lasers for silicon photonic transmitters
V. Conclusion

Tb/s era is coming

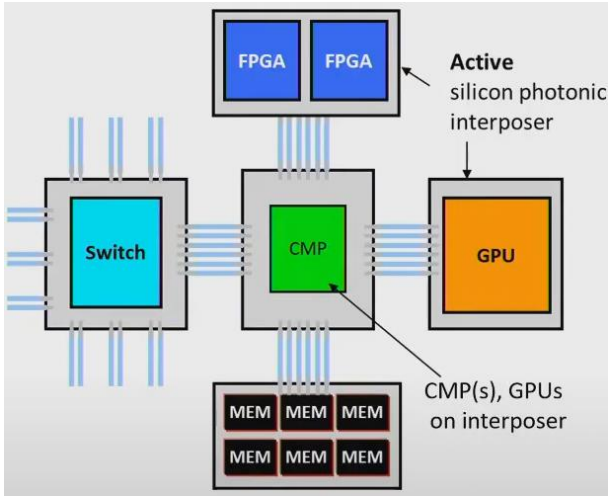


Optical I/O for Silicon Photonics Chiplet

- High BW ➡ Multi-Tb/s per wire
- Low power consumption ➡ <1pJ/s

Ultra dense WDM links on chip system

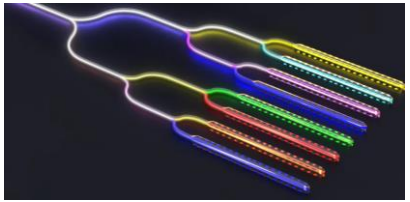
- High speed ring modulator (feedback controlled)
- Co-packaged or monolithic integrated with EIC
- For lasers:
  - **Small footprint, high density**
  - **Low power consumption**
  - **Multi λ laser source**
  - **On chip，temperature insensitive**

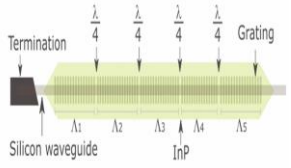


Courtesy to Karen Bergman, Columbia University

Multiwavelength Lasers

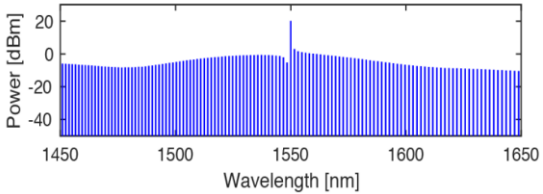
- DFB arrays/ cascade DFB
- DUV lithography defined grating
- Heterogeneous integrated on Si

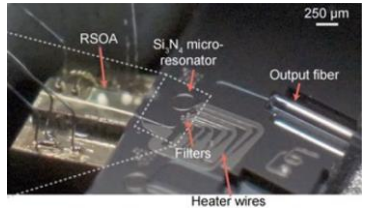




intel

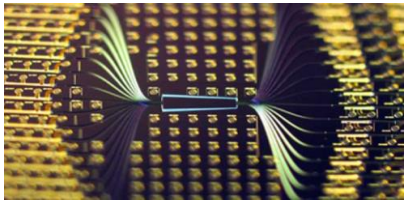
- Kerr frequency combs
- Ultrawide BW





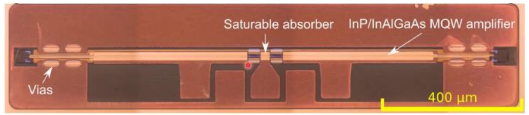
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

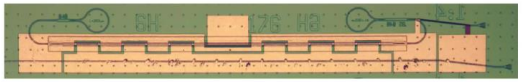
- DFB arrays
- High channel power
- External laser module



AyarLabs

- Mode-locked lasers
- Flat-top spectrum
- Heterogeneous integrated on Si

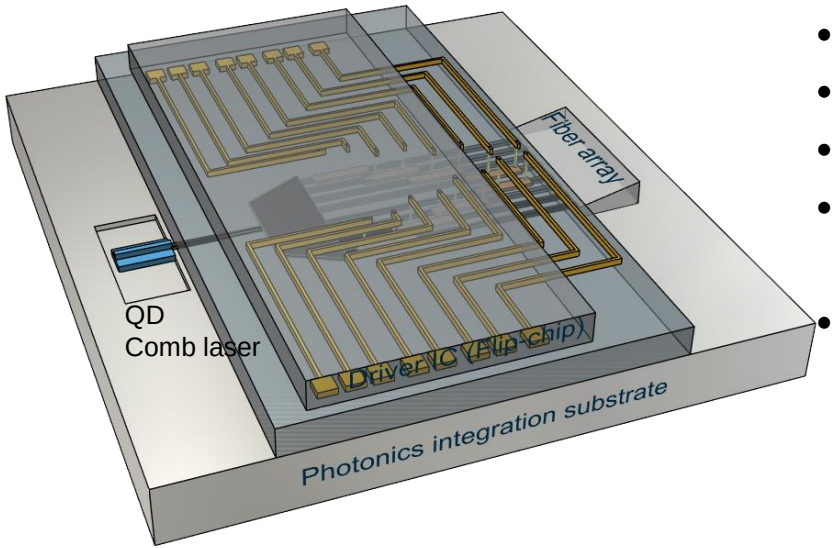


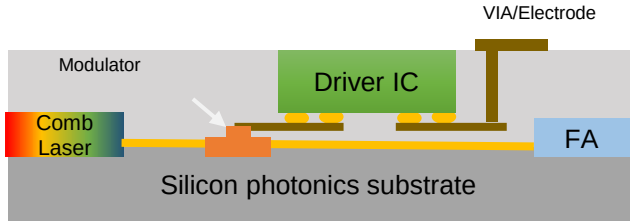


GHENT UNIVERSITY

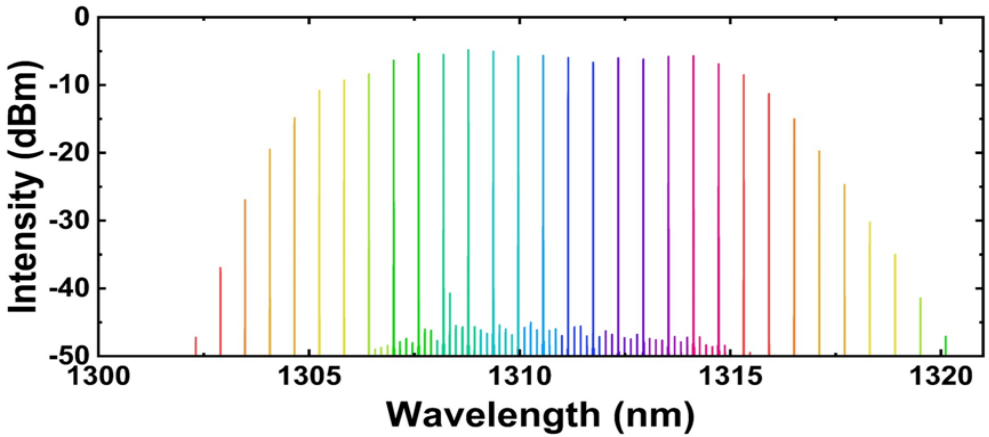
Hewlett Packard Enterprise

QDs comb laser's solution



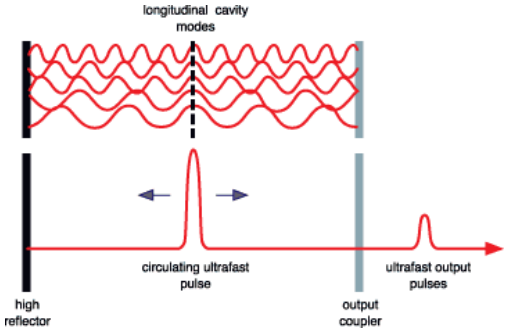


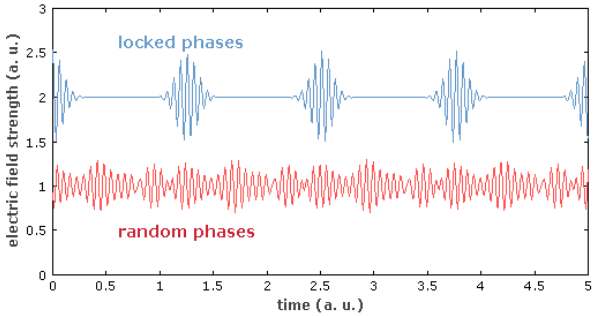
- One comb laser source to replace laser arrays
- One driver, onetime coupling (hybrid integration)
- Lower power consumption, Small footprint
- Uniform comb spacing (+/- 5GHz)
- Large bandwidth (8 lines 200GHz spacing; 16 lines 100GHz spacing)
- Monolithically integrate with Si



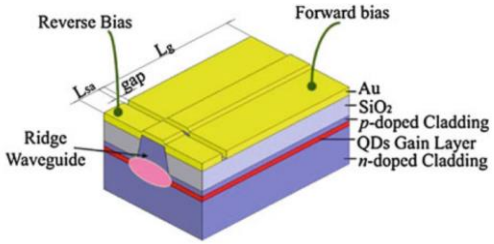
Comb Laser: mode-locked laser

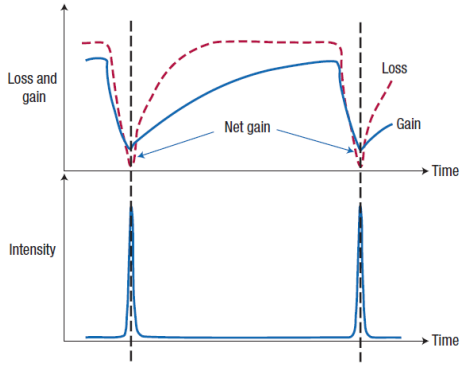
Phase, amplitude and frequency/timing stability are required when using a laser as an optical clock.





Passive mode-locked uses a saturable absorber incorporated into the laser cavity





IEEE Photonics Technology Letters 19.11 (2007)

Nature photonics 1.7 (2007): 395

QDs mode-locked laser

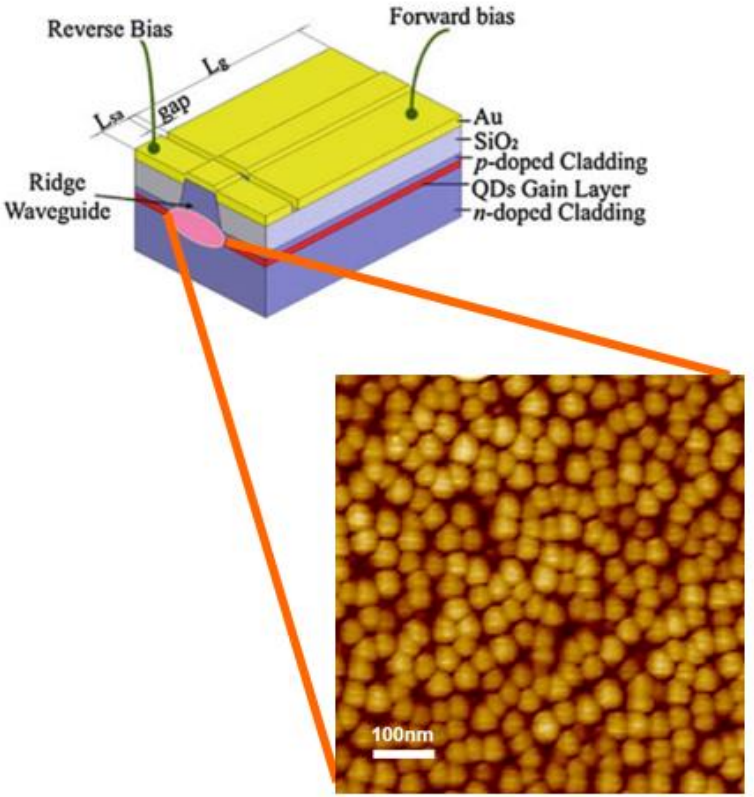
Quantum dots are an ideal media for a semiconductor mode-locked laser (MLL)

- Low threshold current, working near threshold, less spontaneous emission noise
- Temperature insensitivity
- Monolithically grown on Si
- Ultrafast recovery time—shorter pulse
- Inhomogeneous broadening—against gain spectral narrowing effect

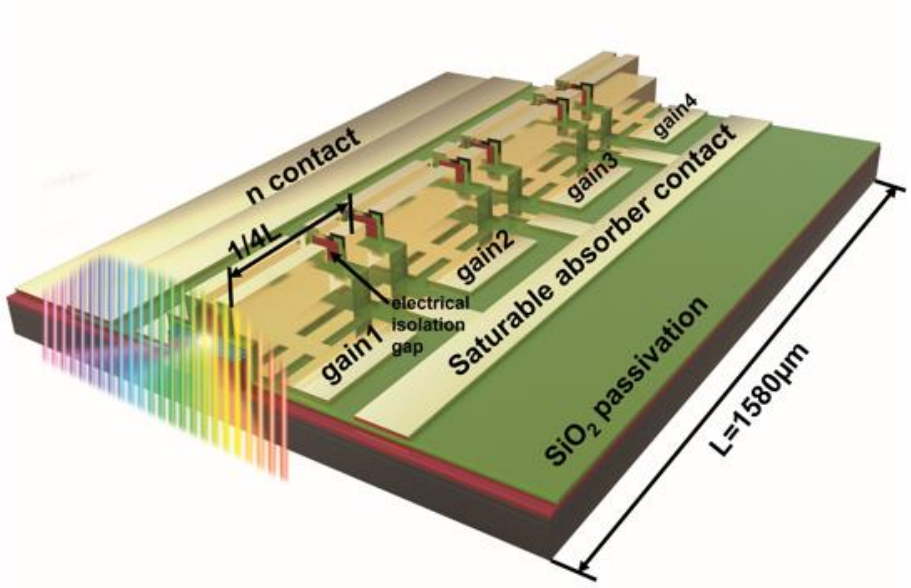
$$\frac{c}{\lambda^2}\Delta\lambda \cdot \Delta\tau = K$$

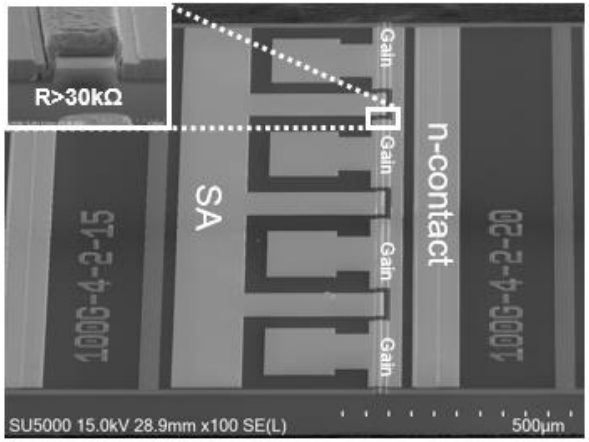
$\Delta\lambda$ Optical spectrum B

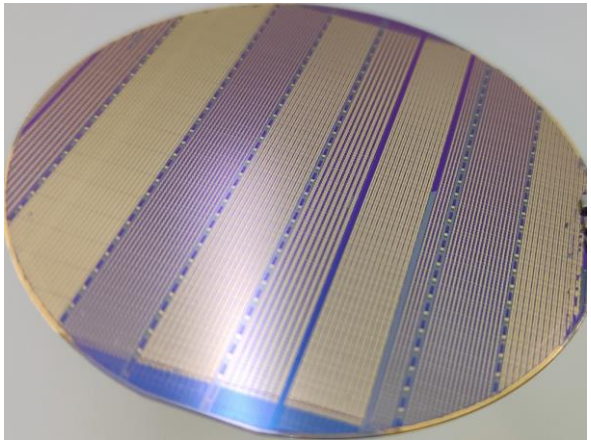
$\Delta\tau$ Pulse duration



4th order CPM comb lasers

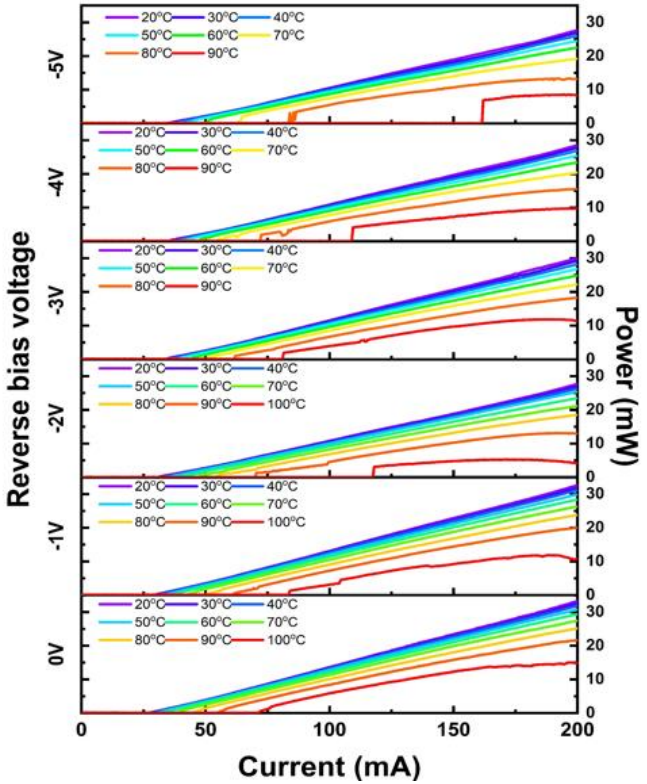


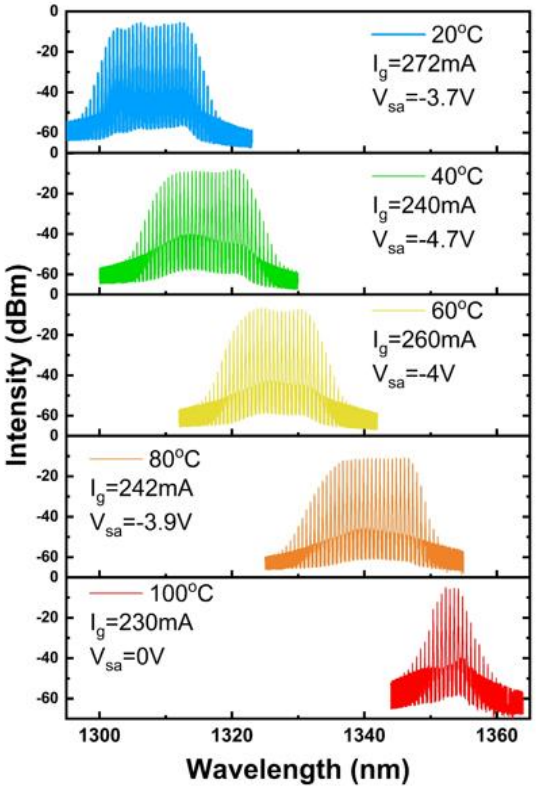




- 100GHz spaced 4th order MLL design
- Electrical isolation R> 30kΩ

4th order CPM comb lasers

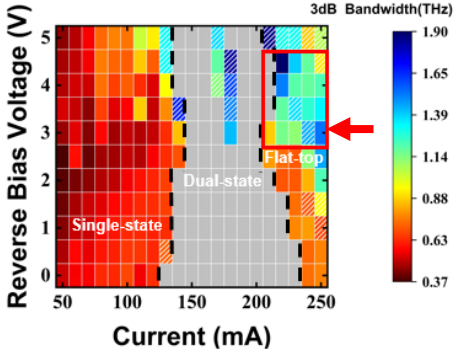


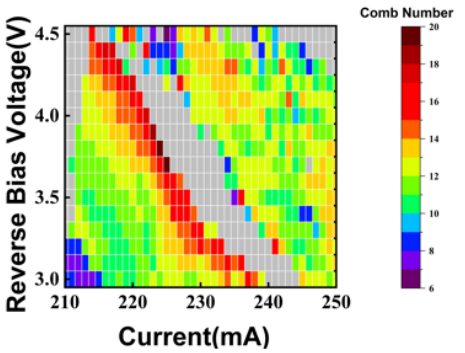


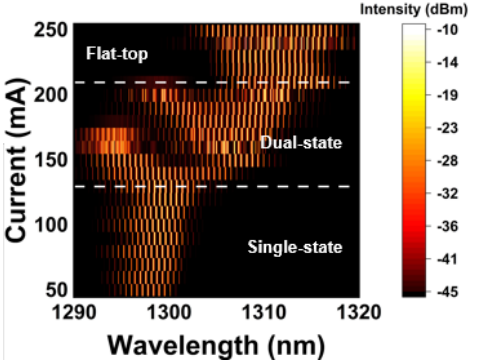
- CW operation temperature up to 100°C
- Flat-top spectrum

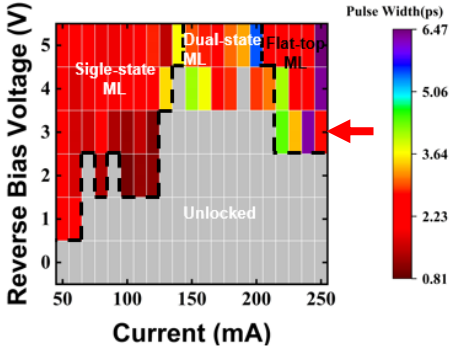
Photonics Res. 10(5) (2022)

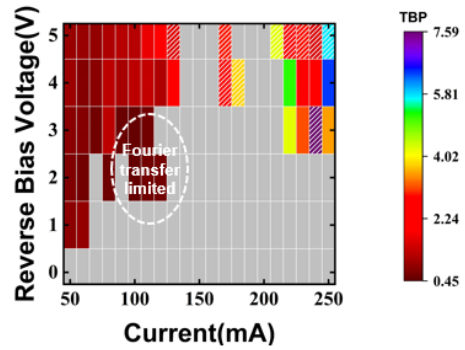
Flat-top operation regime

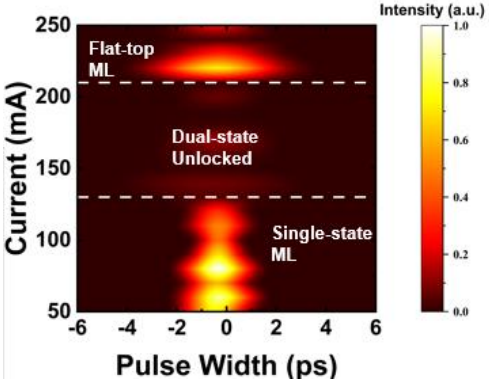










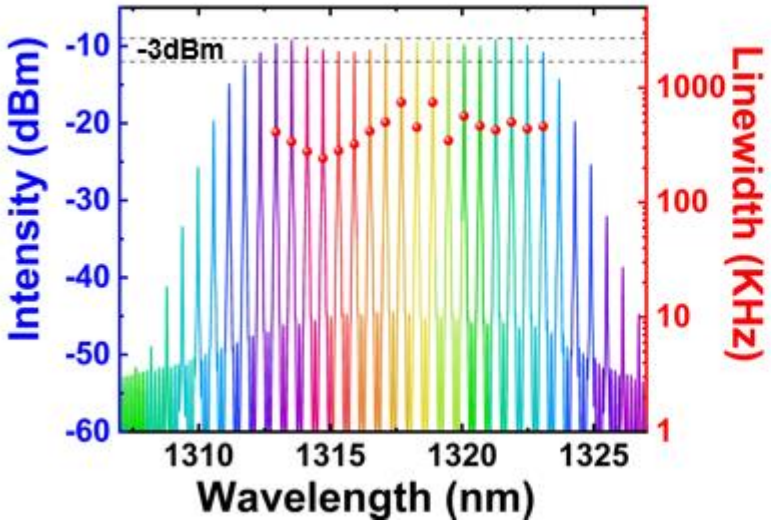


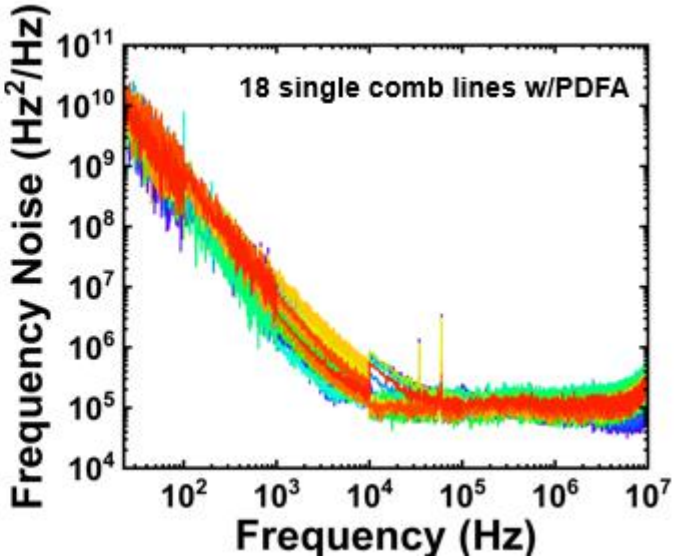
- QDs inhomogeneous broadened comb spectra

Photonics Res. 10(5) (2022)

Flat-top QDs comb laser

I_g=224 mA, V_{SA}=-3.8 V

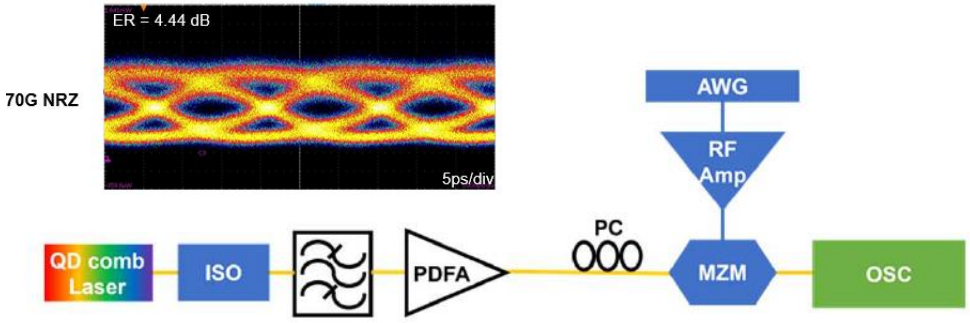




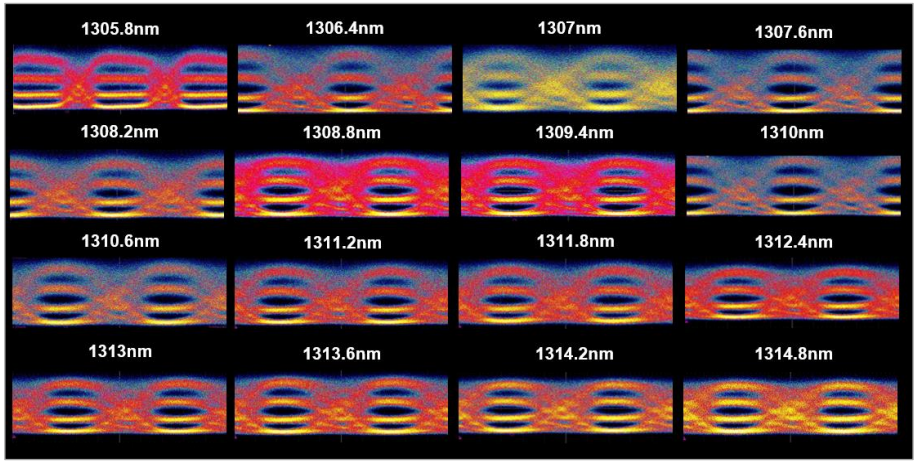
- 20 comb lines within 3dB variation
- Each comb lines has > 35dB SNR
- Single comb line power >1.7mW (excluded insertion loss)
- Average comb linewidth < 440kHz

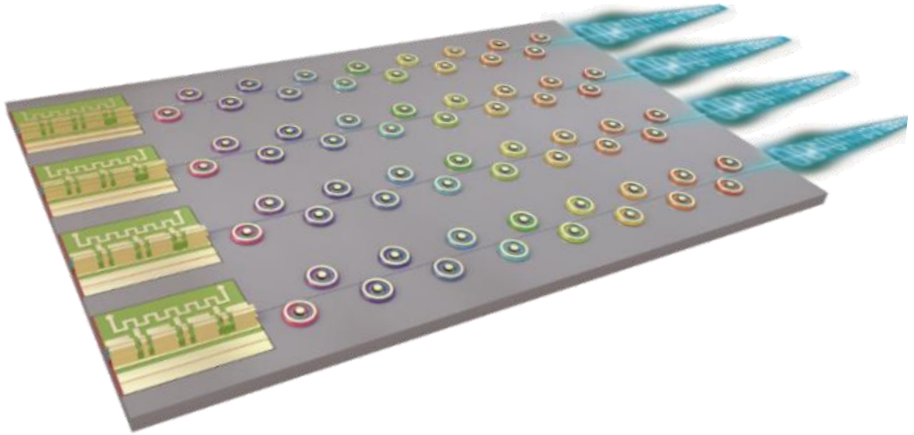
Photonics Res. 10(5) (2022)

B2B transmission characteristics



- 40Gbaud PAM-4
- 70Gbps NRZ
- 20 comb lines: 1.6Tbps capacity





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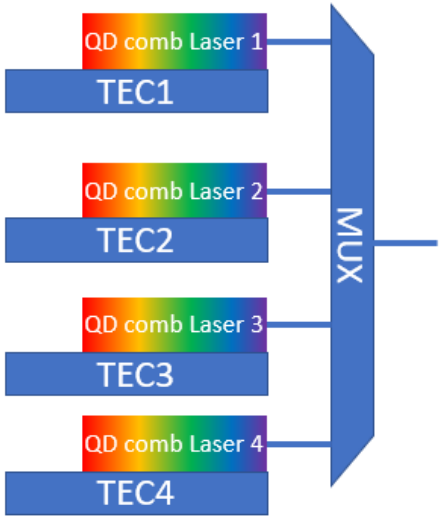
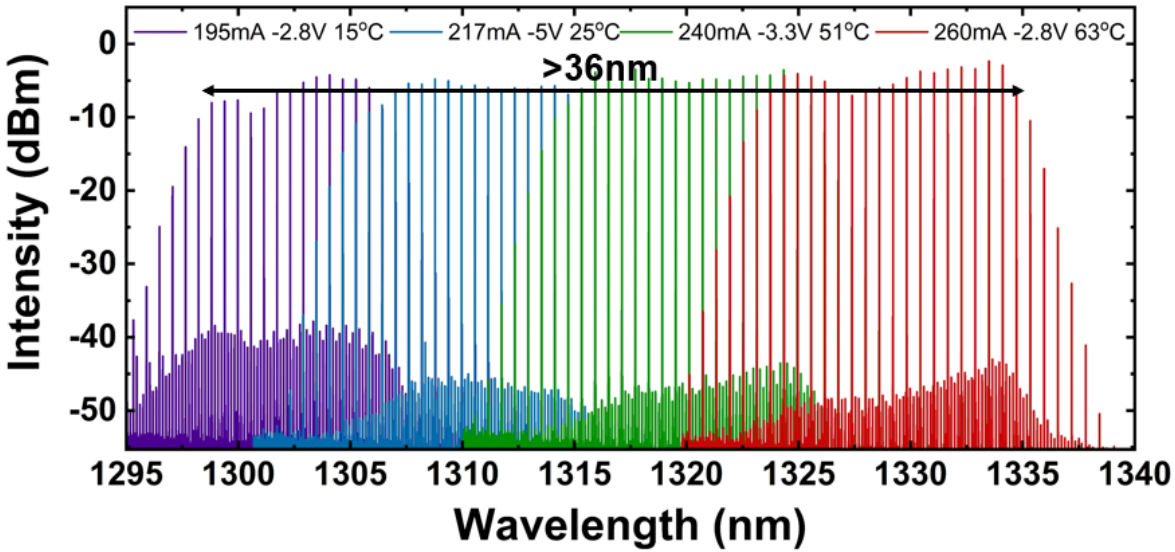
Wavelength expand solution

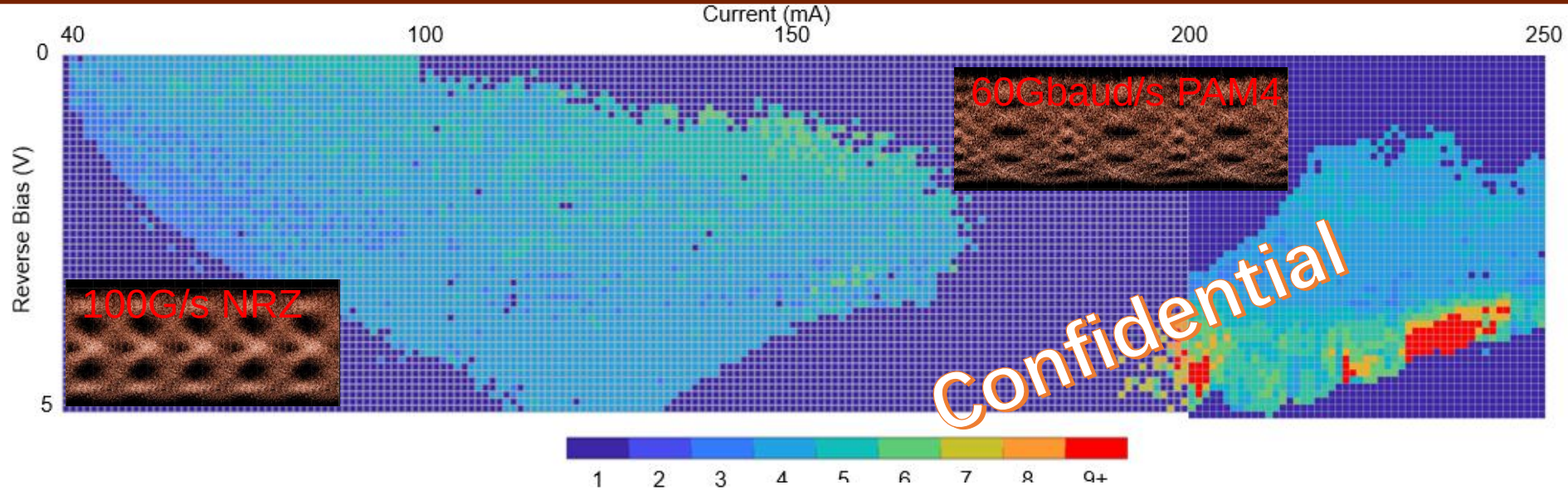




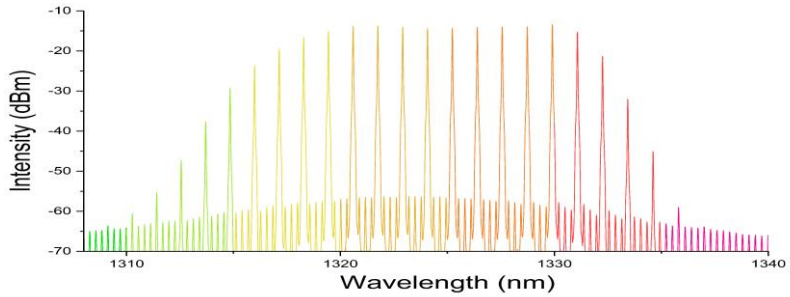
- Adjust temperature to expand comb bandwidth
- 60 comb lines: 4.8Tbps capacity

Photonics Res. 10(5) (2022)

200GHz QDs comb lasers



- 4th order 200GHz QDs comb
- >9 comb lines
- >100 mW output power
- > 80°C CW operation
- 100Gbps NRZ; 60Gbaud/s PAM4



QDs comb vs. DFB arrays

- DFB laser arrays design
- Wavelength spacing: +/- 25GHz
- Power variation: <1 dB
- Wavelength number: 8
- Mode spacing: 200GHz
- Temperature：0-60°C
- Single line power > 10dBm

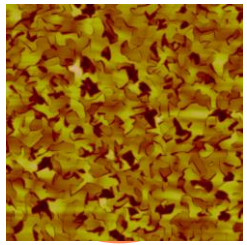
- High order MLL design
- Wavelength spacing: +/- 5GHz
- Power variation: <2 dB
- Wavelength number: 9@200GHz; 20@100GHz
- Mode spacing: 100/200GHz
- Temperature：0-80°C@200GHz; 0-100 °C@100GHz
- Single line power: 5-10dbm

Ideal for ultra-high density, high temperature, mediate output power applications

Epitaxy of III-V on Si

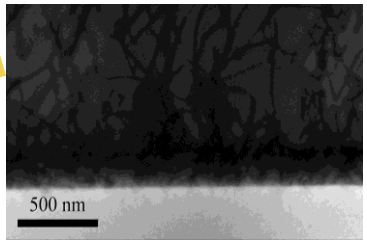
APDs

Polarity difference between III-V/Si



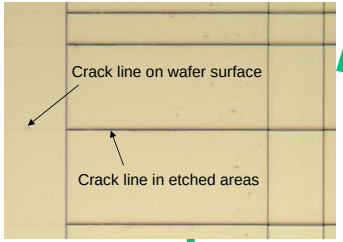
TDs

Lattice mismatch induced high defect density



Thermal Cracks

Thermal expansion contrast caused micro cracks



Approaches

Miscut Substrate 1

- Suppress anti-phase boudaries by using Si substrates with 2 - 6° miscut
- QW dislocation filter structures

Intermediate Layer 2

- GaP or Ge intermediate buffer layers
- Lattice matched system at the III-V/IV interface

Patterned Substrate 3

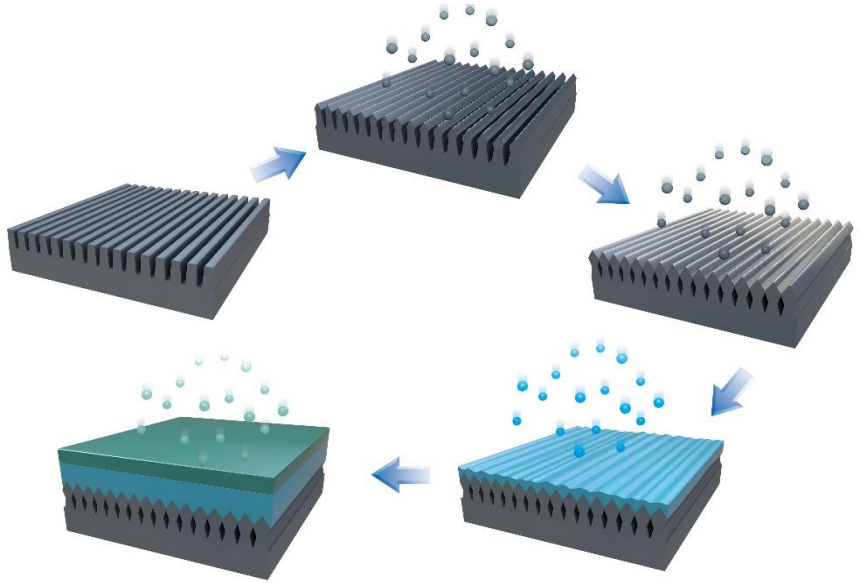
- Patterned V-grooves on standard Si substrates
- CMOS compatible

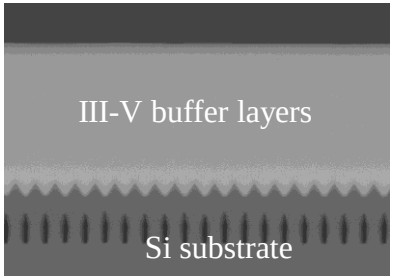
Complicated buffer structures and restricted wafer conditions

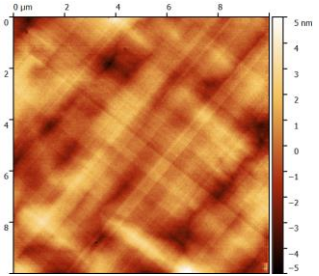
Patterning process induced defects

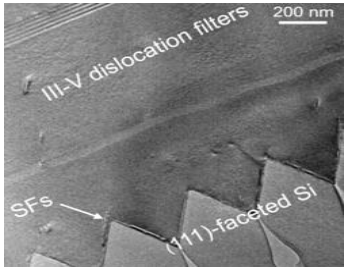
GaAs on (111)-faceted Si hollow structure

- 8-inch Si wafer
- Pattern period 360 nm
- U-shape ridge width ~ 140 nm
- U-shape pattern depth ~ 500 nm
- Homo-epitaxy of Si ~550 nm
- III-V dislocation filter structures
- 2×2 μm^2 AFM roughness: 0.24 nm



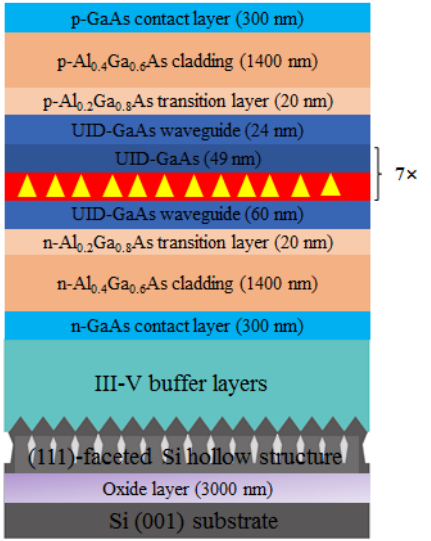


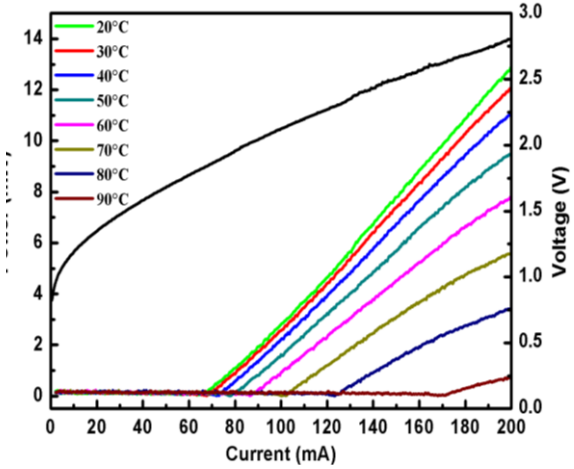


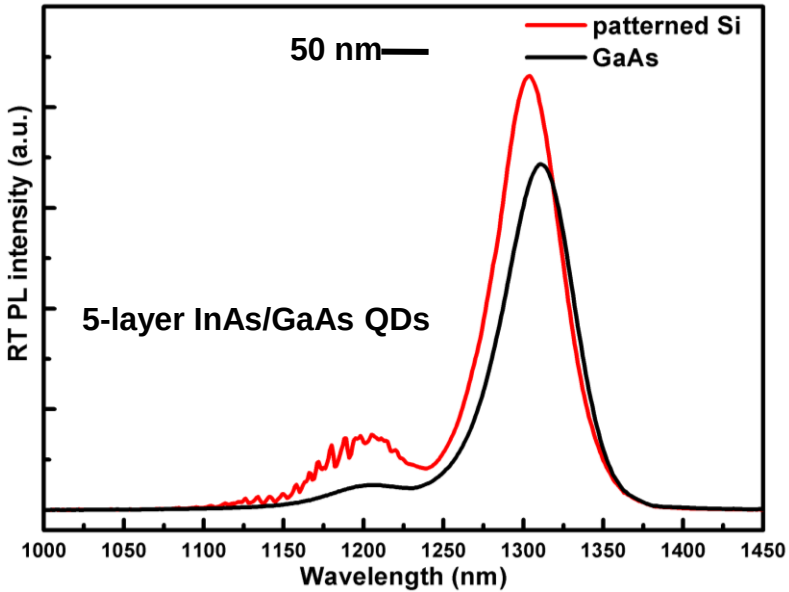


Appl. Phys. Lett. 113, 053107 (2018)
J. Phys. D 55, 405105 (2022)

1.3 μm InAs QDs FP lasers on Si



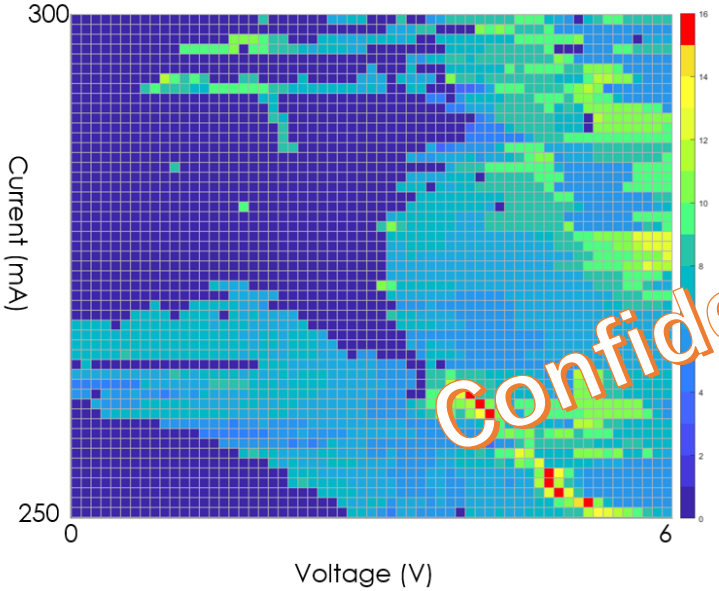




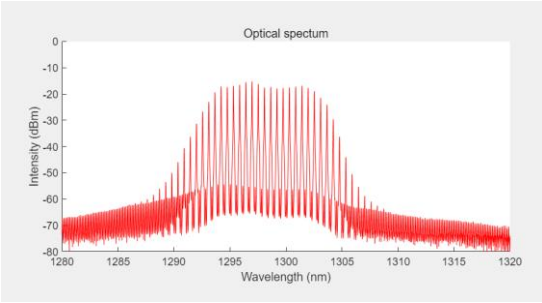
- High density InAs QDs: 3.3×10^{10} cm^{-2}
- Enhanced PL intensity due to Si (111) grating structures
- CW operation up to 90 °C

J. Phys. D 55, 405105 (2022)

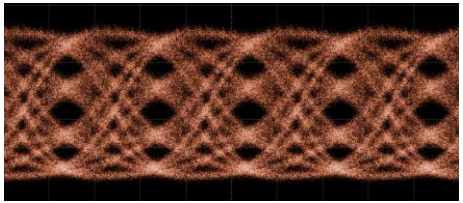
100GHz QDs comb lasers



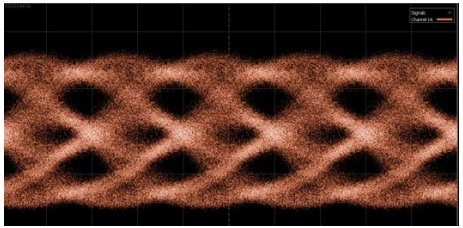
261mA 4.1V



56GbaudPAM4

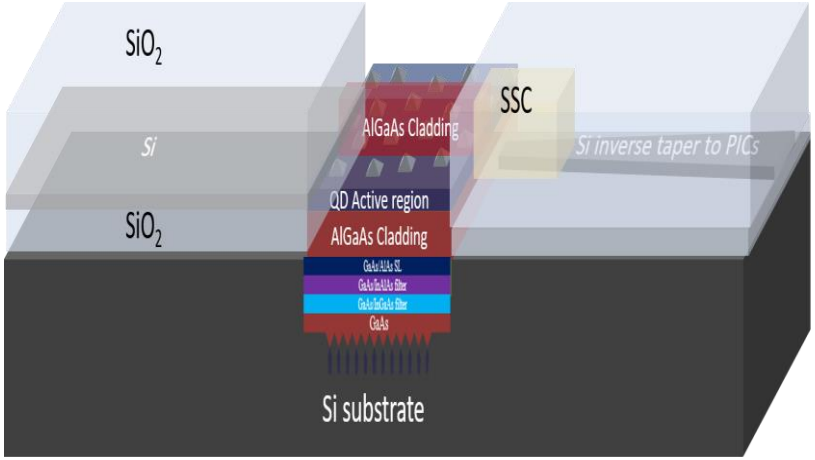


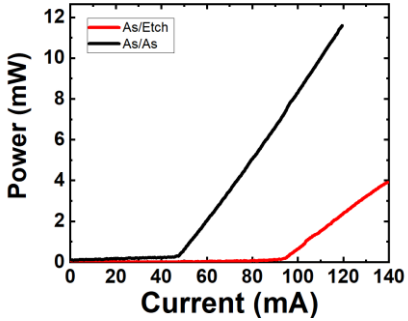
100Gbps NRZ

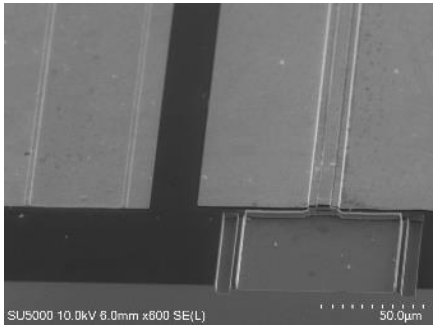


- 4th order 100GHz QDs comb on Si
- >16 comb lines
- > 50 mW output power
- > 75°C CW operation
- 100Gbps NRZ; 56Gbaud/s PAM4

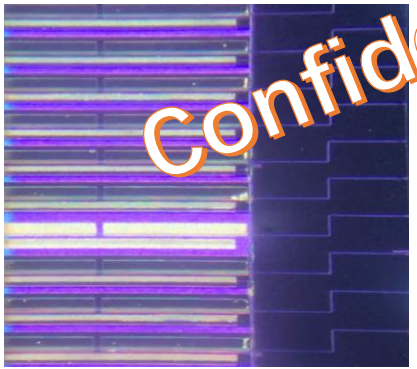
Monolithically integrated QD comb lasers for silicon PIC

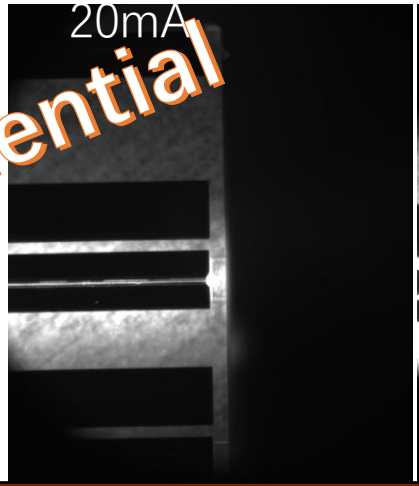


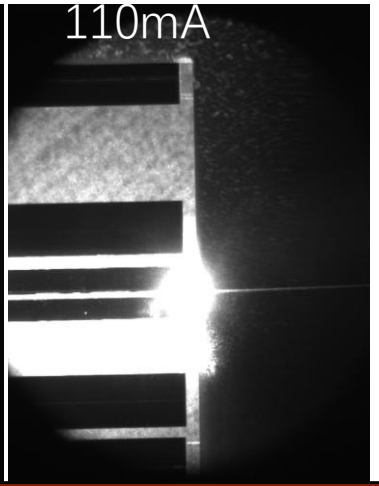




- Embedded FP Lasers in the SOI trench
- Light is coupled out of Si waveguide



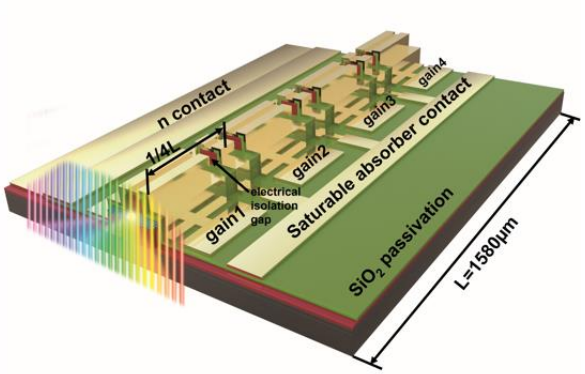


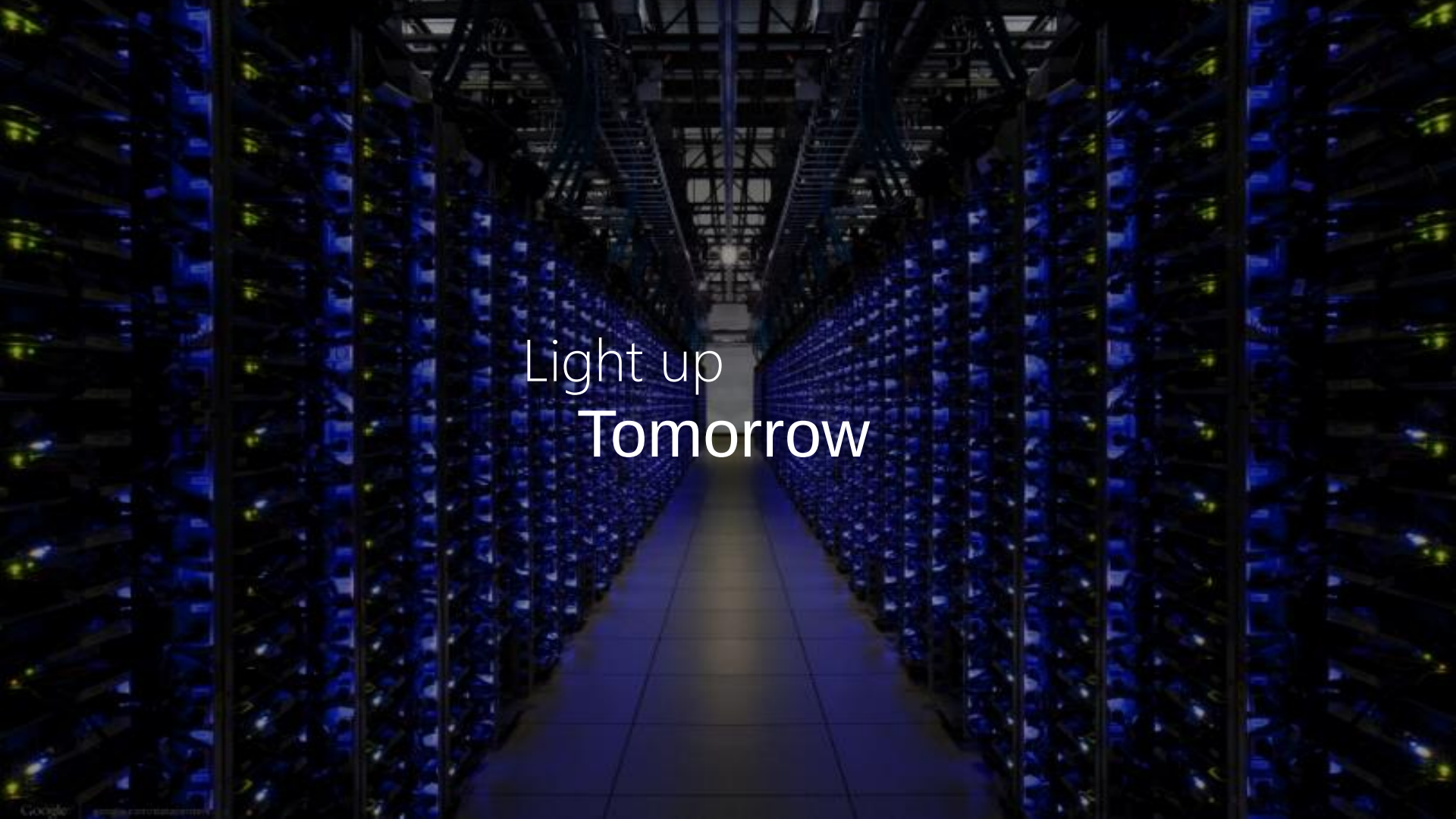


Conclusion

- Comb laser source solution is proposed to provide energy efficient multi-wave light source for Tb/s WDM system
- 100GHz spaced InAs QDs comb laser is achieved by directly grown on Si
- 200GHz spaced InAs QDs comb on GaAs
- SOI embedded QD comb lasers are proposed on Si platform

Thanks to the students, postdocs and staff members!




Light up
Tomorrow