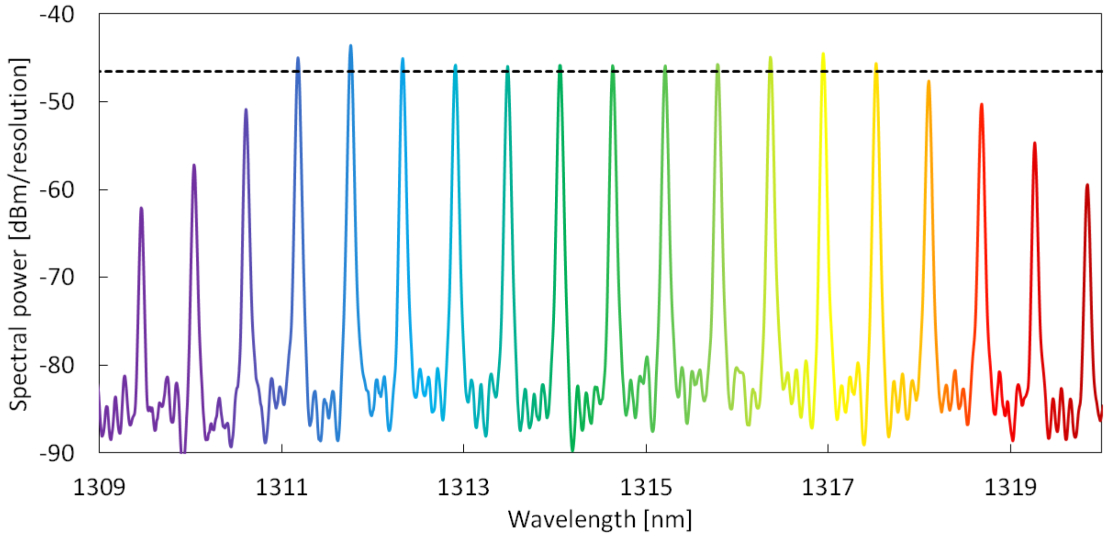
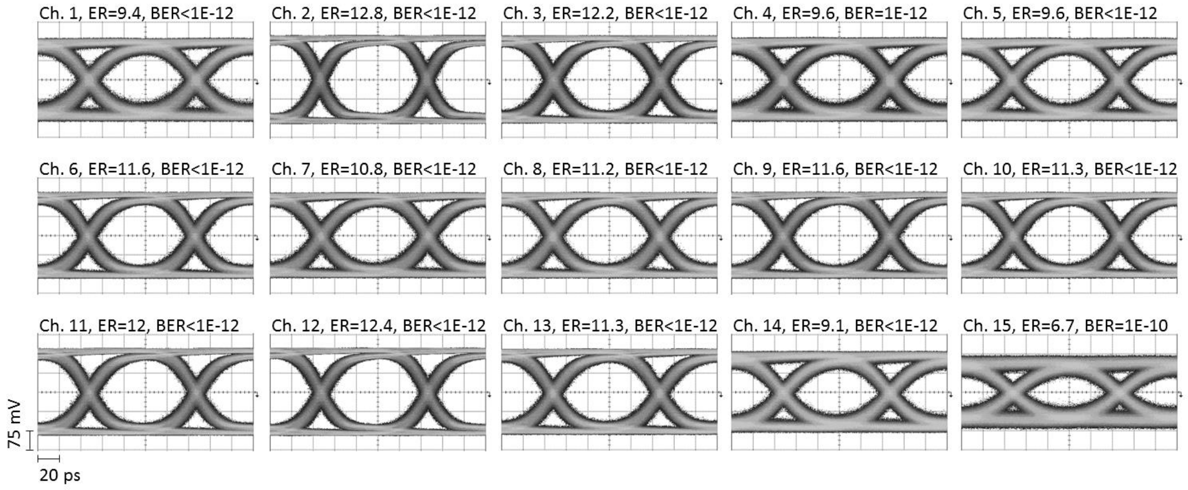
On-Chip Hybrid Silicon Quantum Dot Comb Laser With 14 Error-Free Channels





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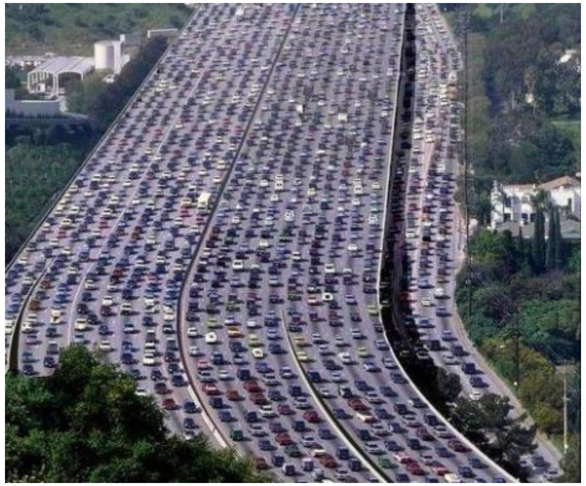
Comb Lasers

– Exascale computers require two flavors of optical links
  – Node-to-node (low-medium traffic): Maximize efficiency → 4-16 single-λ lasers (ring laser array)
    – Turn off channel(s) you don't need
    – Imperfect channel spacing
  – Port-to-port (high traffic): Maximize bandwidth → **Comb Laser**
    – Single device (2-4 terminals)
    – Multiple λ within 3 dB of peak λ, constant channel spacing
    – Always on, even if you do not use all channels

Node-to-node

Port-to-port



Comb laser requirements

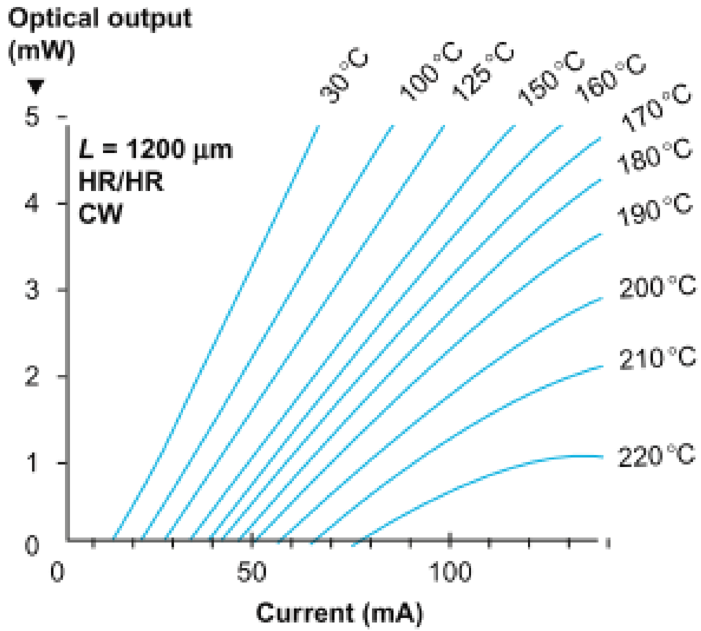
- Operation at high temperature
- Wide gain bandwidth
- Low amplitude noise in ***<u>!EACH!</u>*** comb line

  → **Quantum dot lasers …**

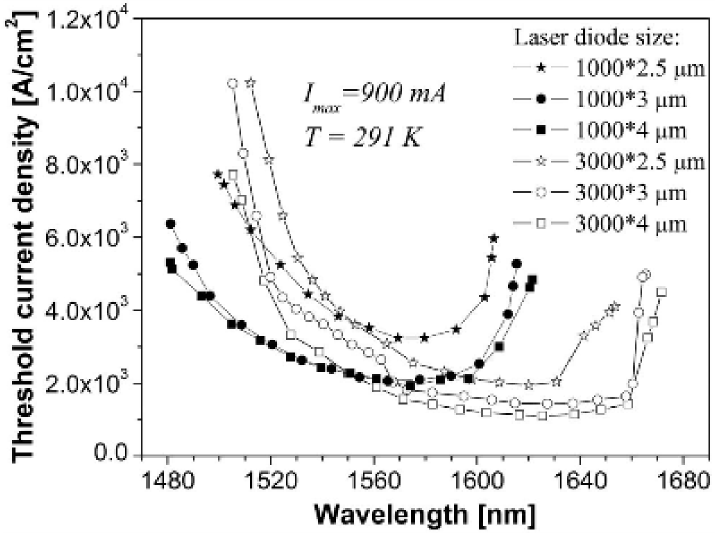
- Integration with high quality passives
  - Gratings, splitters, rings, …
- High yield, volume manufacturing
- On 300 mm wafers

  → **… on silicon**

Don't use Si **just** as a carrier, take advantage of its excellent passives!



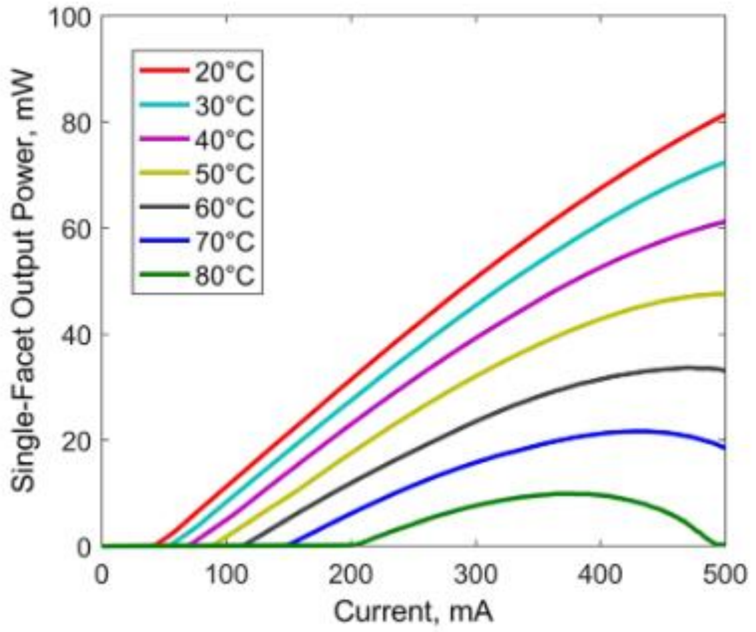
220 °C CW:
QD Laser Inc., 2011



166 nm tuning range:
Ortner et al., APS, 2006

QD integration on silicon

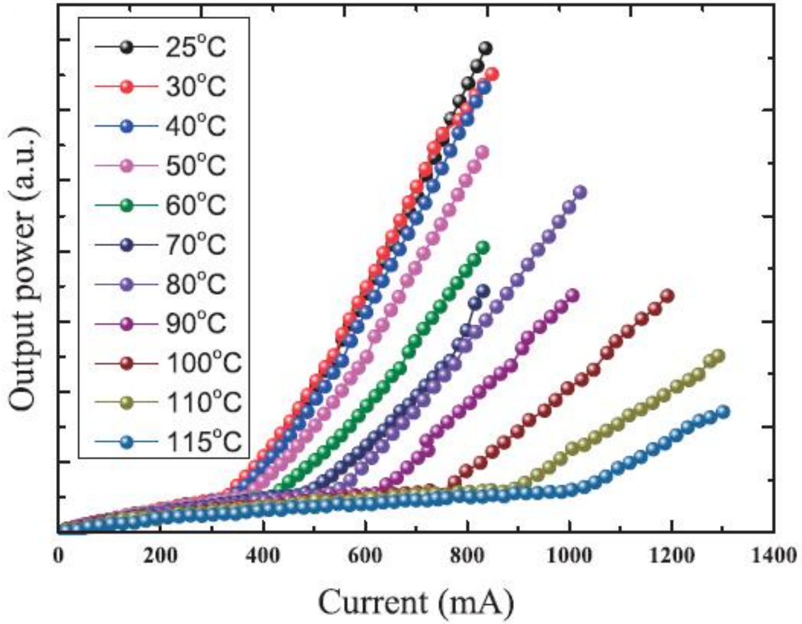
Growth



- Lasing to 80 °C
- No coupling to Si (thick buffer layer)

Norman et al., OE, 25, 3927, 2017

Bonding



- Coupled to Si
- CW @ 25 °C
- Pulsed to 115 °C

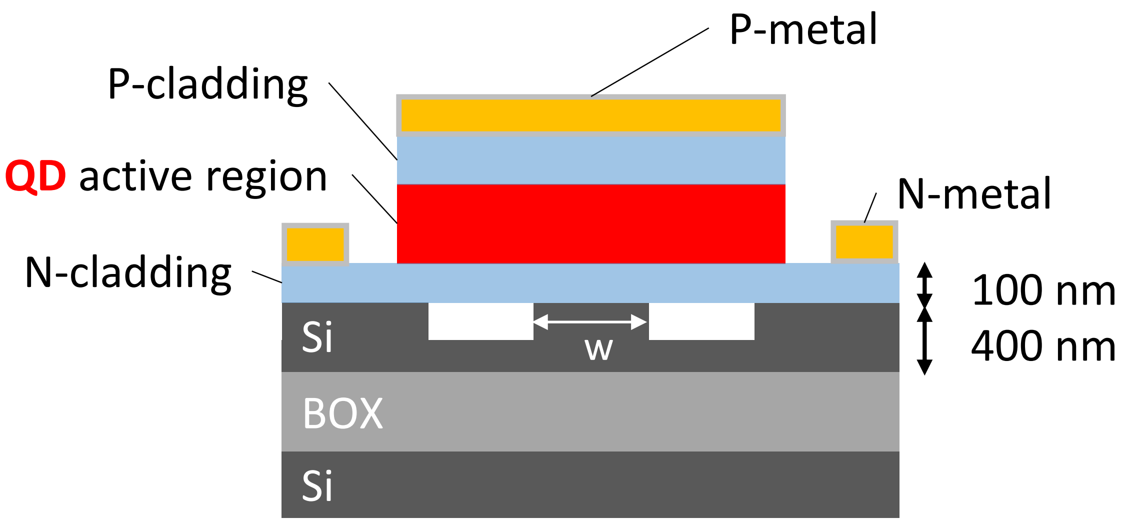
Jang et al., Applied Physics Express, 2016

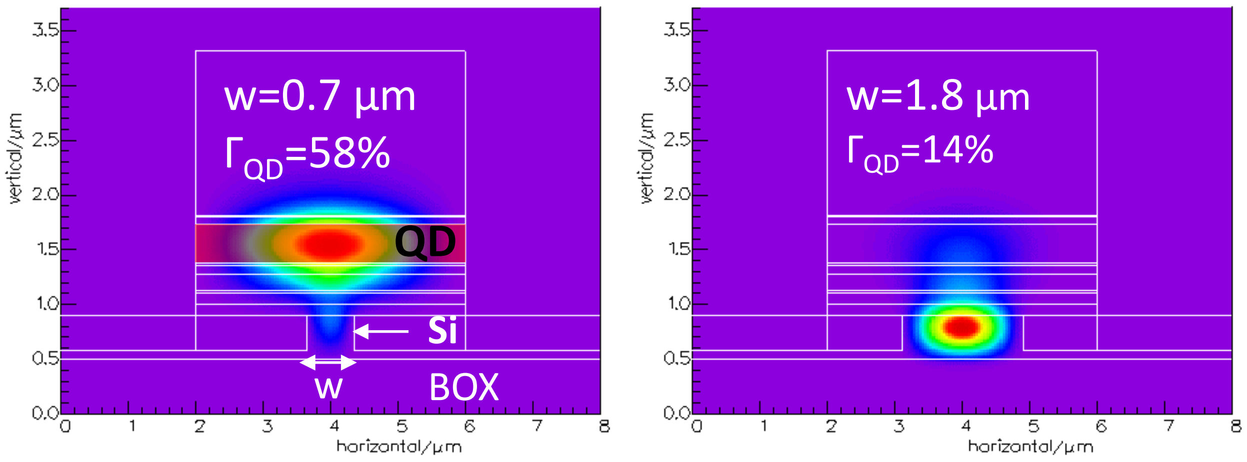
Our approach

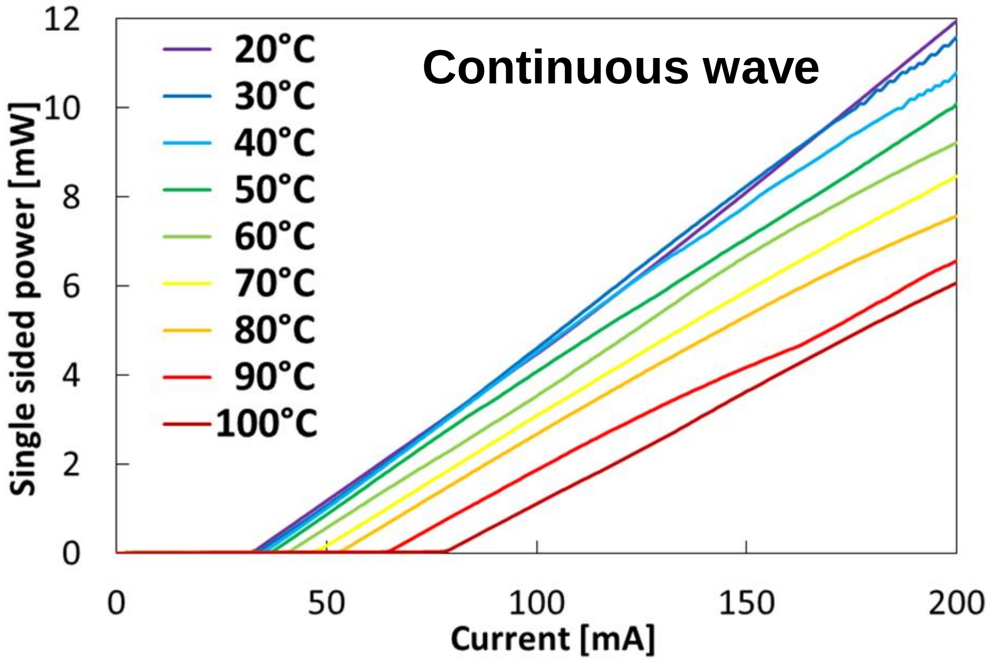
– Bonding III/V to SOI

– Design layer thicknesses for efficient coupling between Si and III-V

– Adjust QD confinement through Si WG width







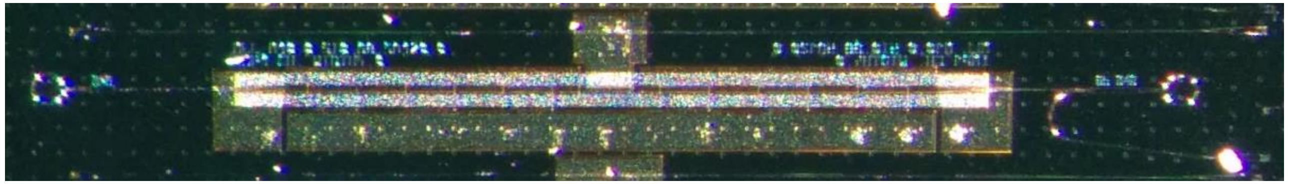
Kurczveil et al., Optics Express, 2016

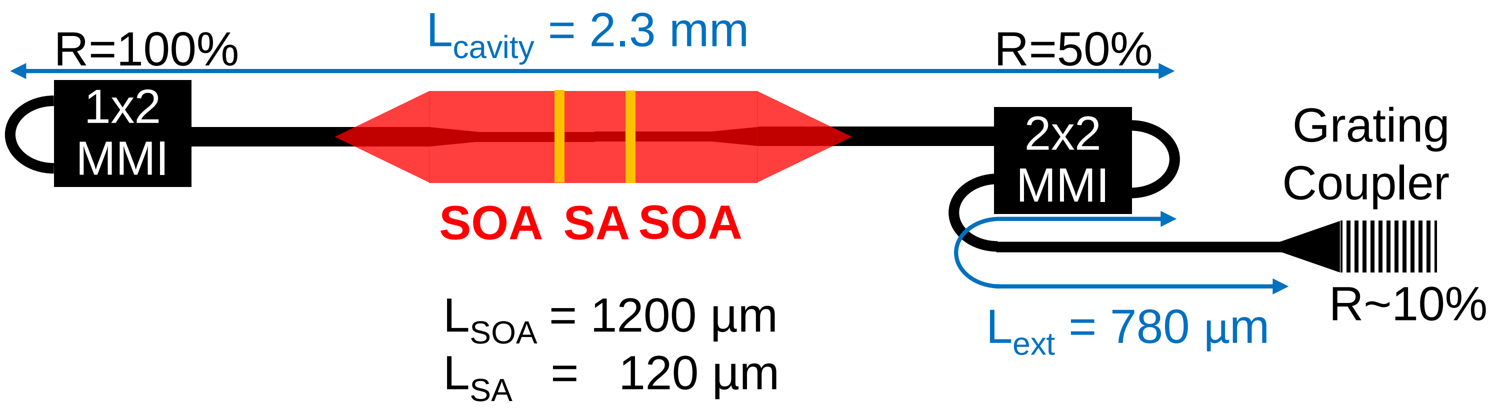
Device design

– Single cavity would have tradeoff between gain and FSR
  – Need FSR ~ 50-80 GHz → L ≤ 750 µm → aggressively short (QDs have lower gain than QWs)

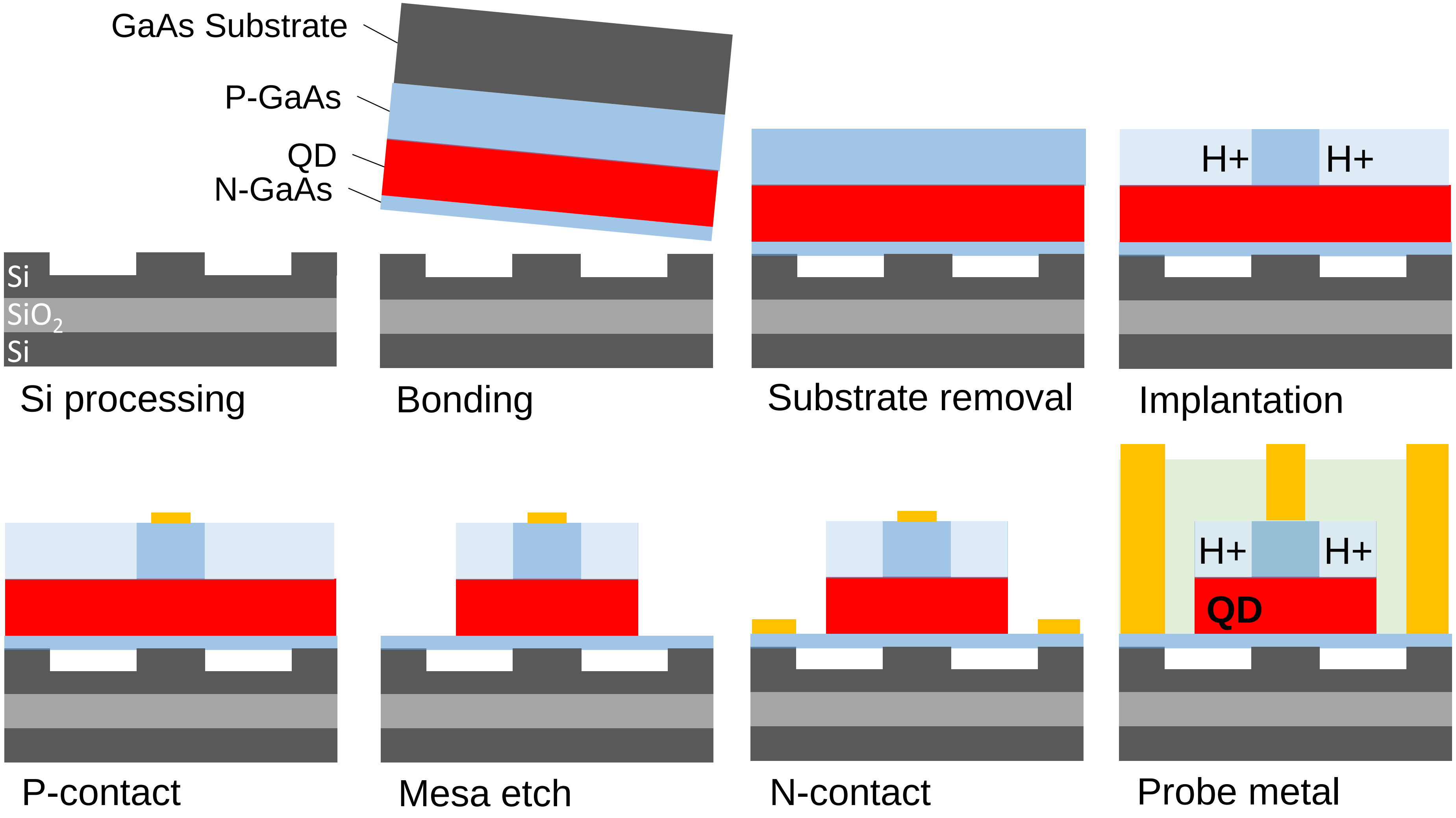
→ Coupled cavity
  – FSR_{cavity} = 16.8 GHz, FSR_{ext} = 50.5 GHz → **FSR_{Laser} = 101 GHz**

– Fully integrated
  – No dicing/polishing



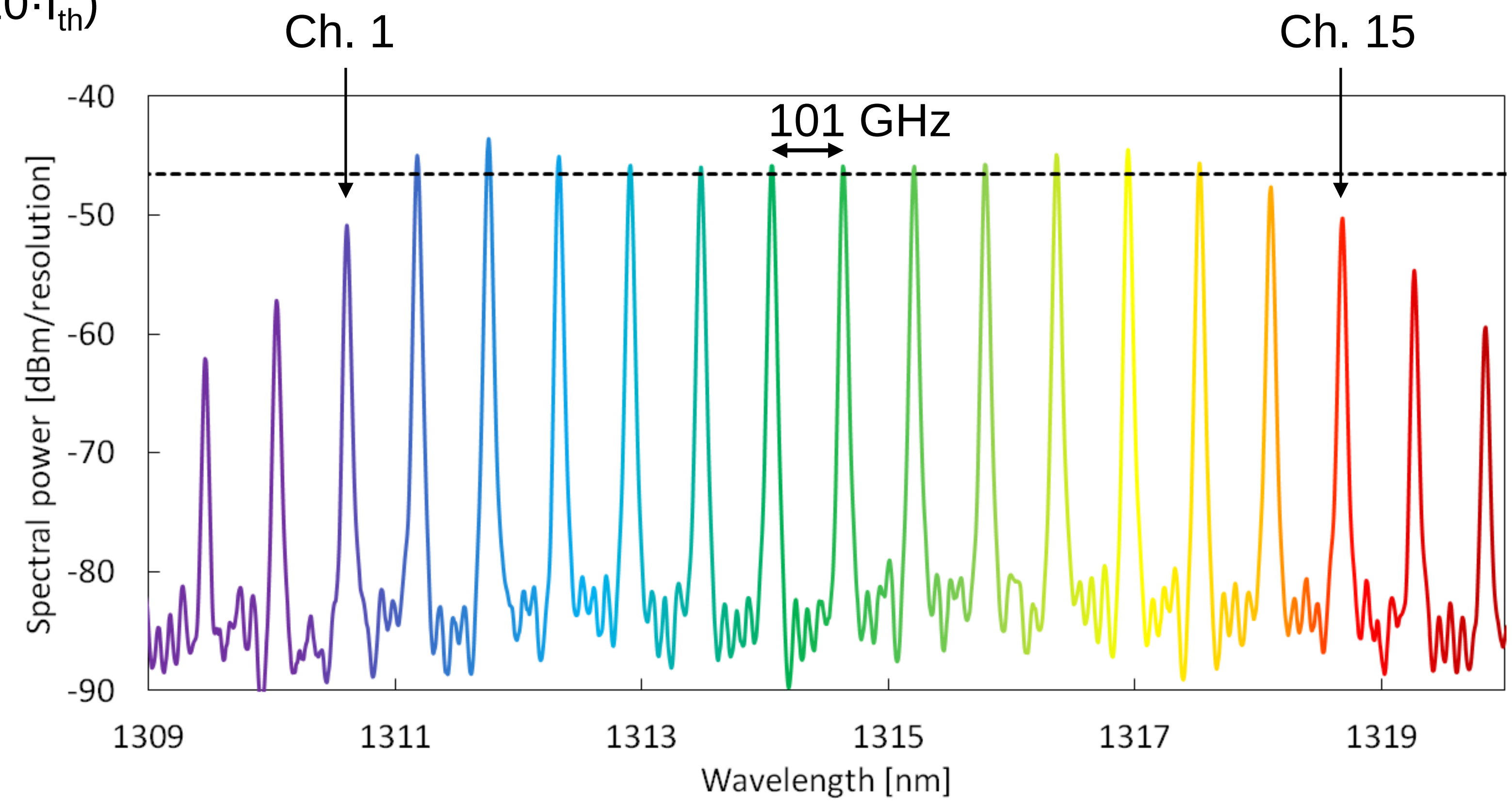


Process


GaAs Substrate
P-GaAs
QD
N-GaAs
Si
SiO2
Si
Si processing
Bonding
Substrate removal
H+
H+
Implantation
P-contact
Mesa etch
N-contact
H+
H+
QD
Probe metal

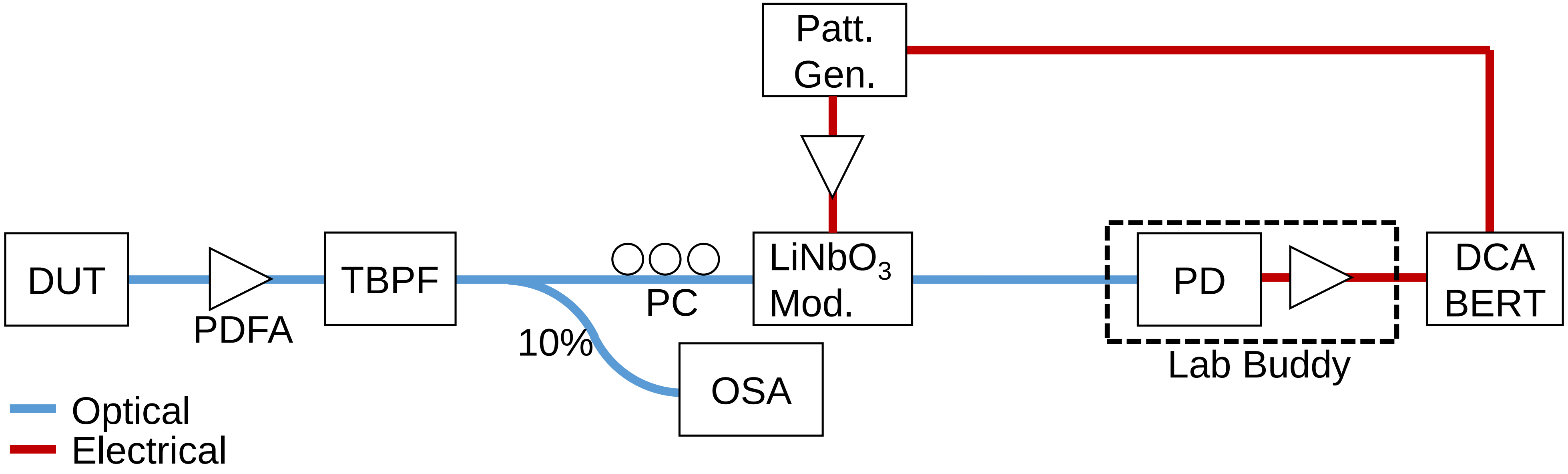
Data – Optical Spectrum

SOA: 395 mA (~10·I_{th})
SA: -6.2 V
P_{out}: ~-9 dBm
T: 25 °C

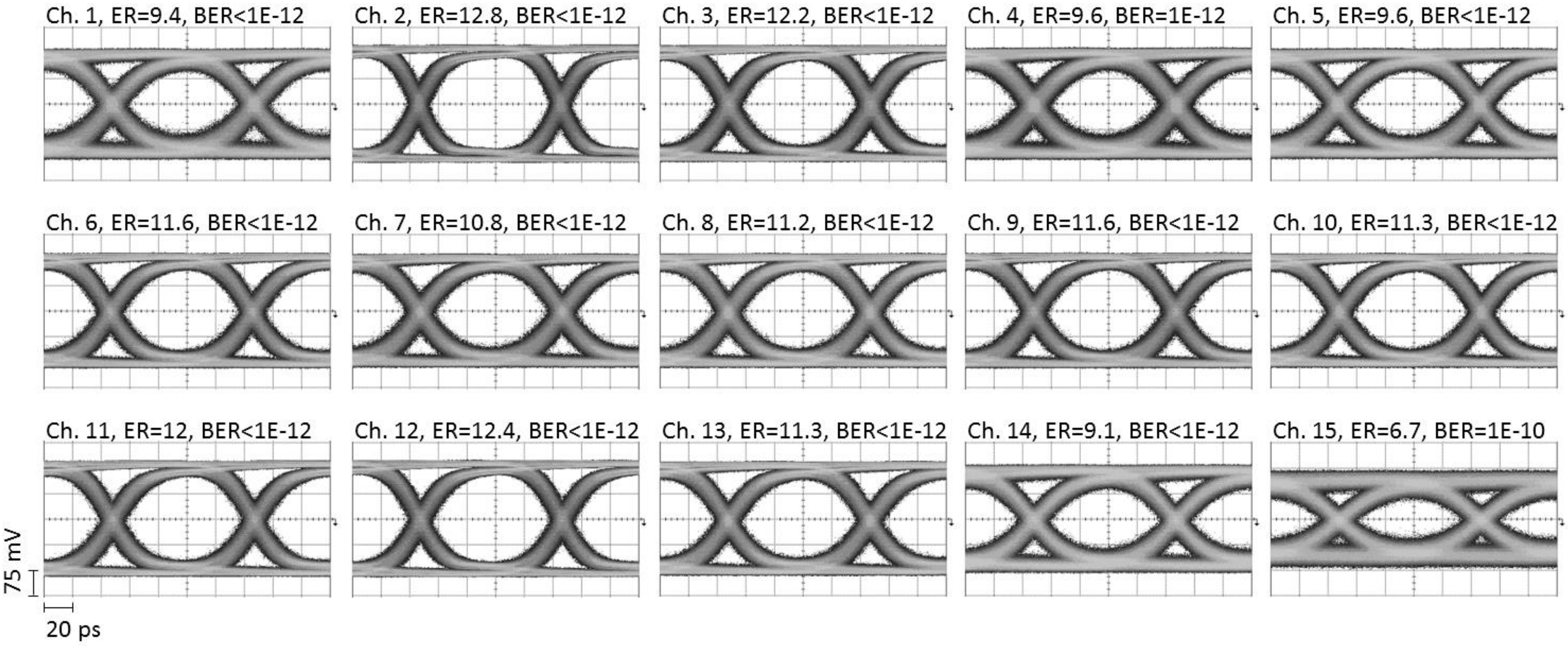


Setup for eye diagram

DUT → amplify → filter out **!one!** λ → ext. modulator → eye diagram

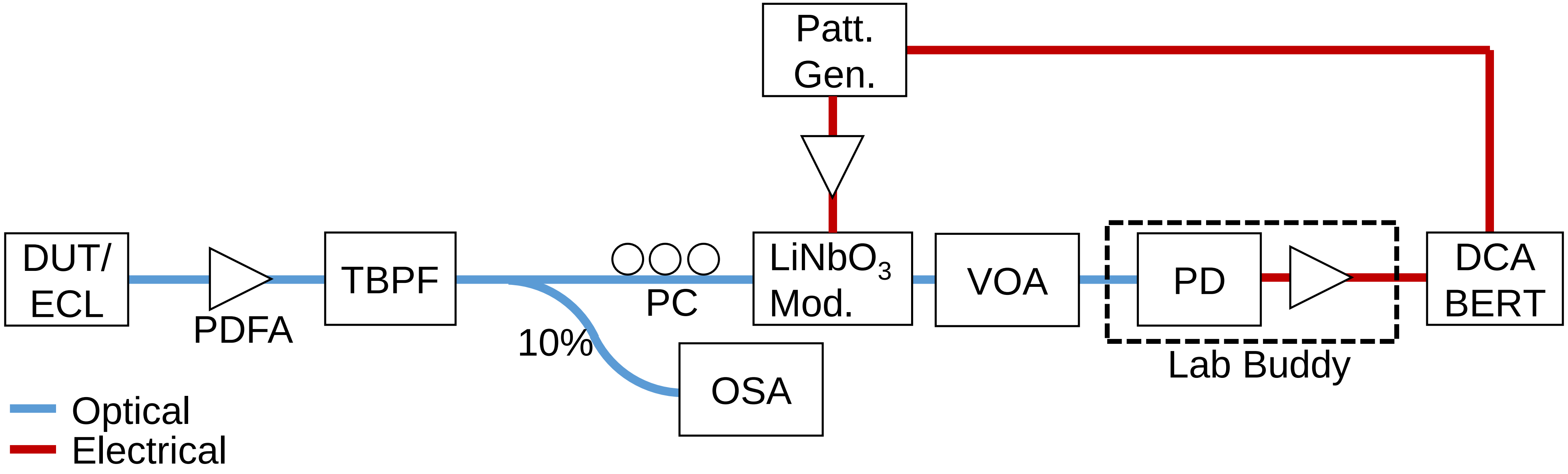


Data – Eye Diagrams (10 Gb/s)



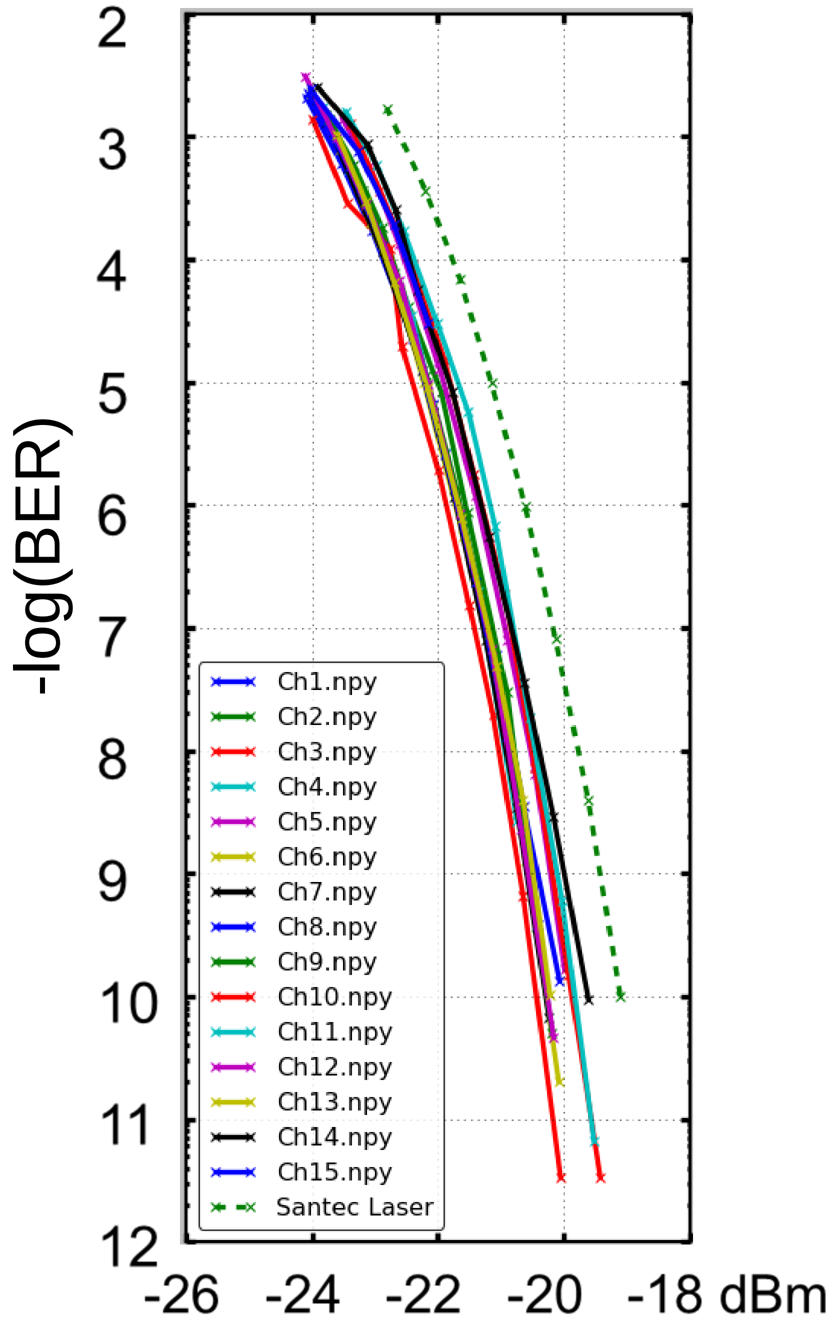
Setup for BER

Same setup as before, except we add a VOA
DUT → amplify → filter out **!one!** λ → ext. modulator → VOA → BER



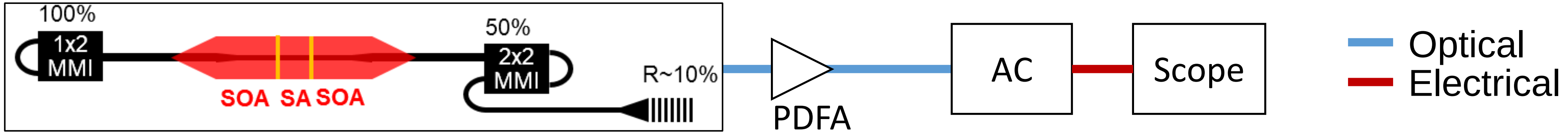
Data – BER

– ≤10^{-10} in all channels
  – Because of 3 dB insertion loss of VOA
  – ≤10^{-12} in 14 channels without VOA
– 0.5 dB improvement over commercial external cavity laser
  – Due to gain/ASE/saturation dynamics of optical amplifier (multi-λ vs. single-λ)
– QW-based laser would be limited by mode partition noise
  – Couldn't use individual comb lines for each channel

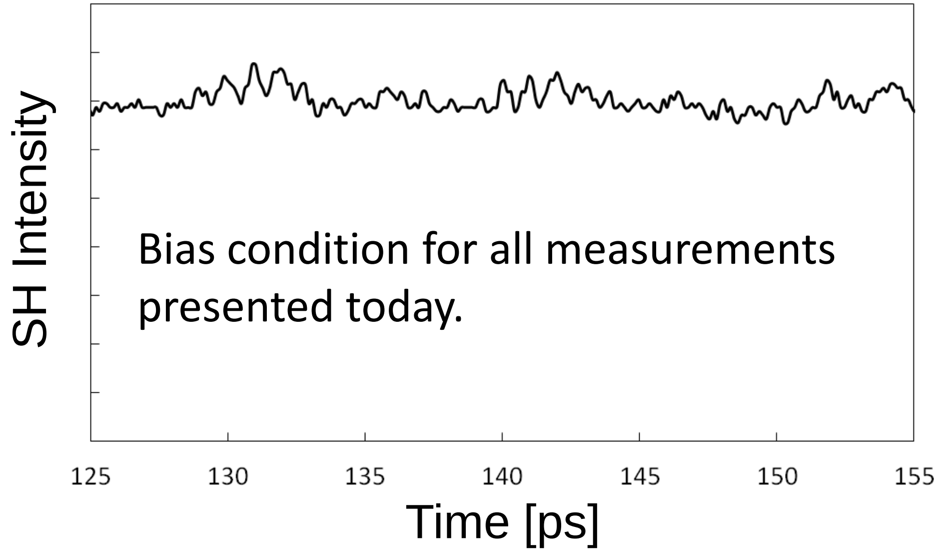


Data – Time Domain (Autocorrelation)

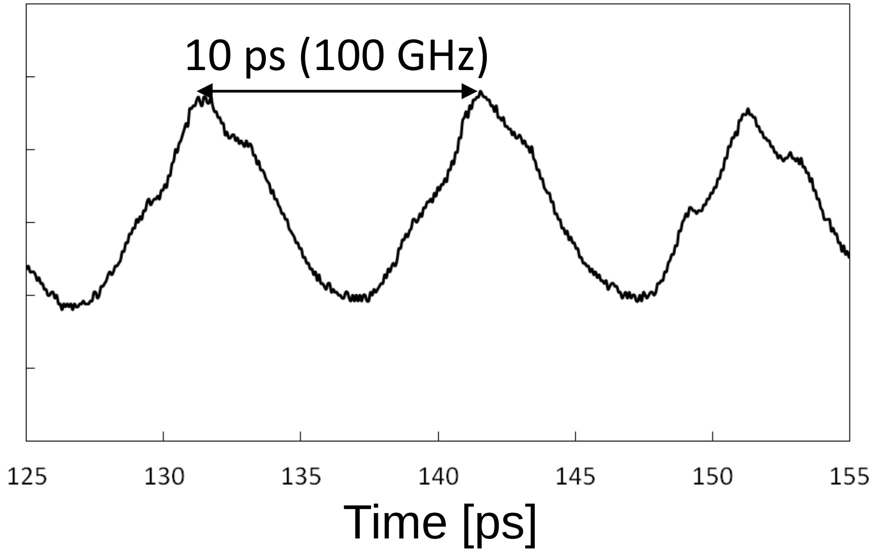
– Optical output is pulsed vs. CW depending on DC bias conditions



DC bias: 395 mA, -6.2 V → CW optical



DC bias: 370 mA, -4.6 V: pulsed optical



At same average power, pulsed laser has higher instantaneous power → worse reliability?

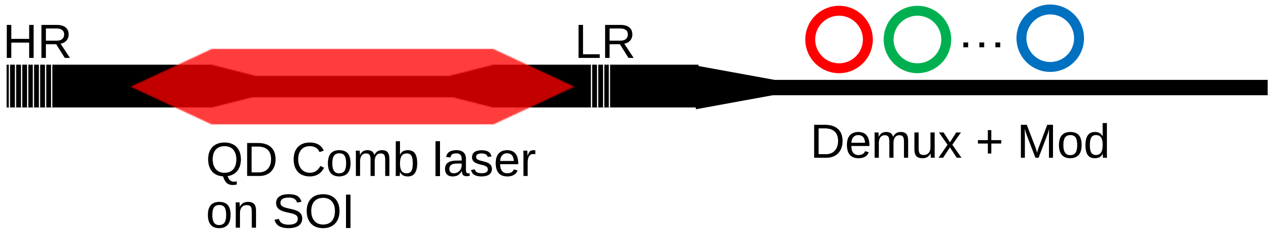
Summary

– Demonstrated a QD comb laser on SOI (12-14 channels)

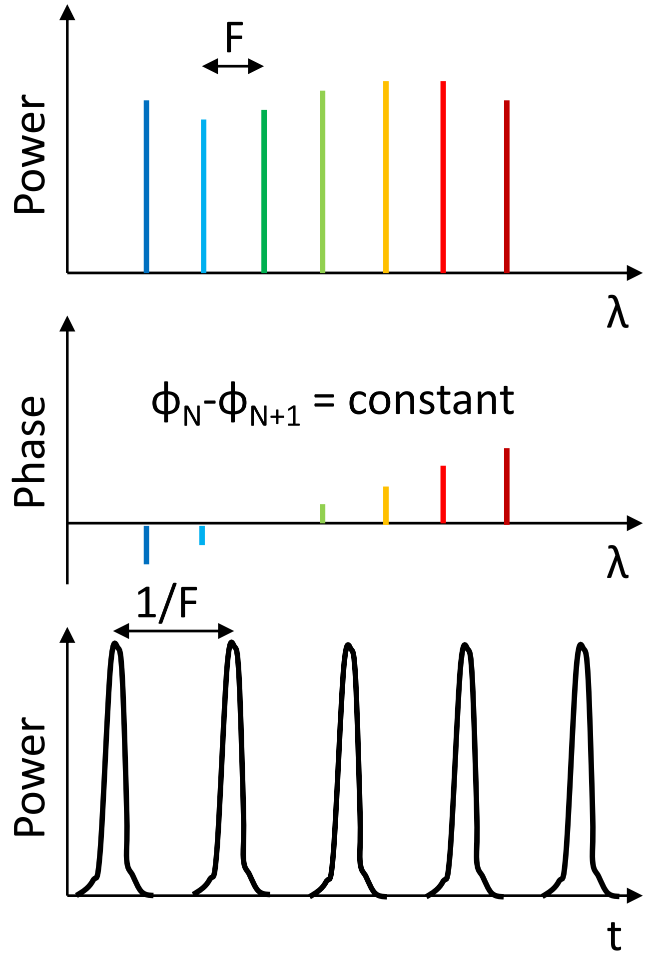
– On-chip mirrors, grating coupler → Wafer-level testing

Future work

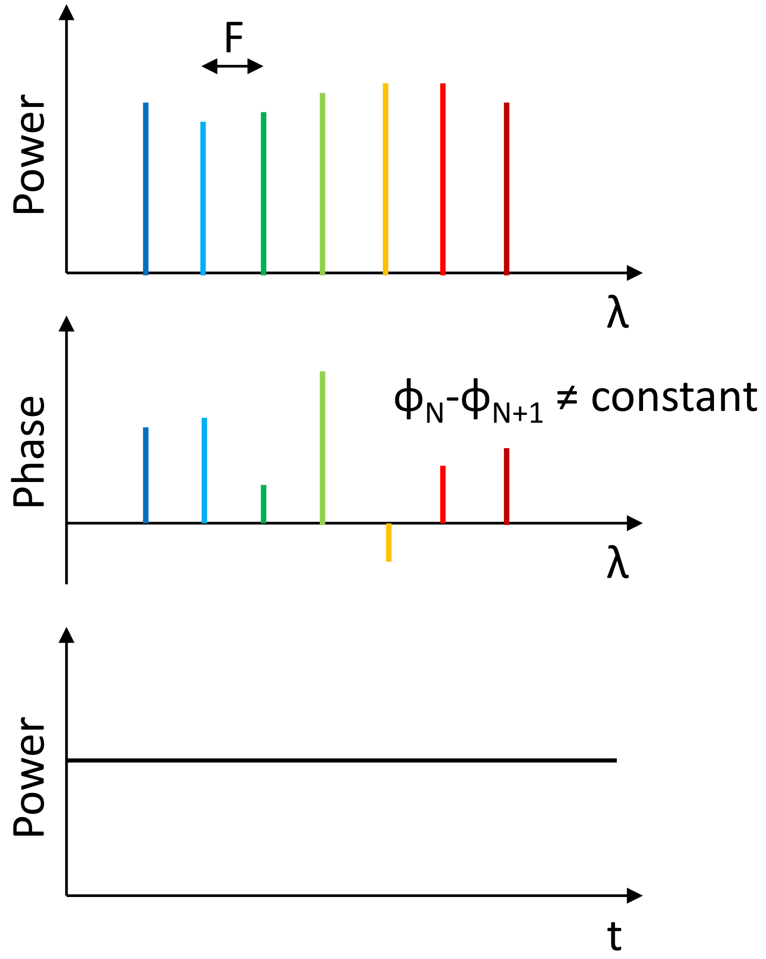
– Improve passives
  – GC
  – Mirror
– Integrate ring modulators
– Increase number of channels (dispersion engineering)



Back up



Temporal mode locking



Frequency mode locking

Comb mechanism

– SHB, FWM, gain compression, inh. gain. broadening, Kerr nonlinearity, …

Literature References

QD

–M. Dong et al., “Traveling Wave Model for Frequency Comb Generation in Single-Section Quantum Well Diode Lasers,” JQE, 53, 6, 2017

–M. Gioannini et al., “Self-generation of optical frequency comb in single section Quantum Dot Fabry-Perot lasers: a theoretical study,” arXiv, 1707.06561v1, 2017

QW

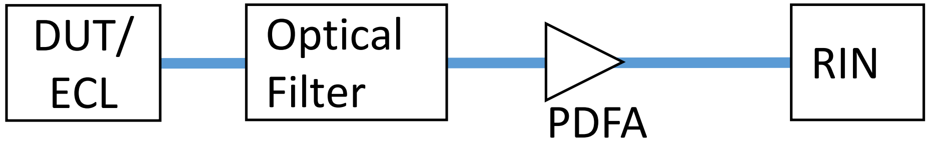
–K. Sato, “Optical pulse generation using Fabry–Pérot lasers under continuous-wave operation,” JQE, 9, 5, 2003

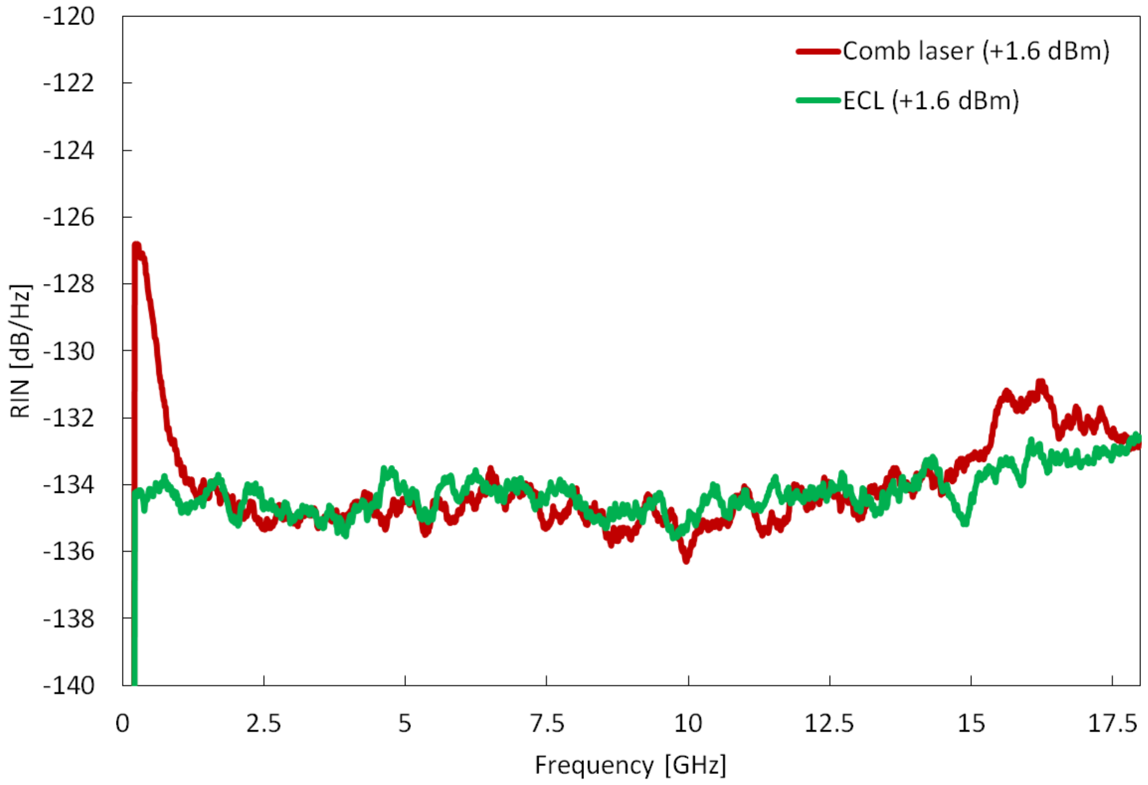
Bulk

–L. F. Tiemeijer et al., “Passive FM locking in InGaAsP semiconductor lasers,” JQE, SQE-25, 6, 1989

Relative Intensity Noise – 1/2

DUT → filter out **!one!** λ → amplify → measure RIN (for same P_{rec}!)



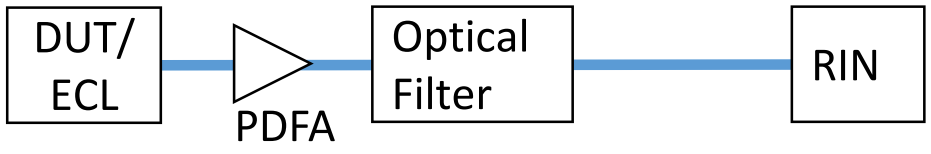


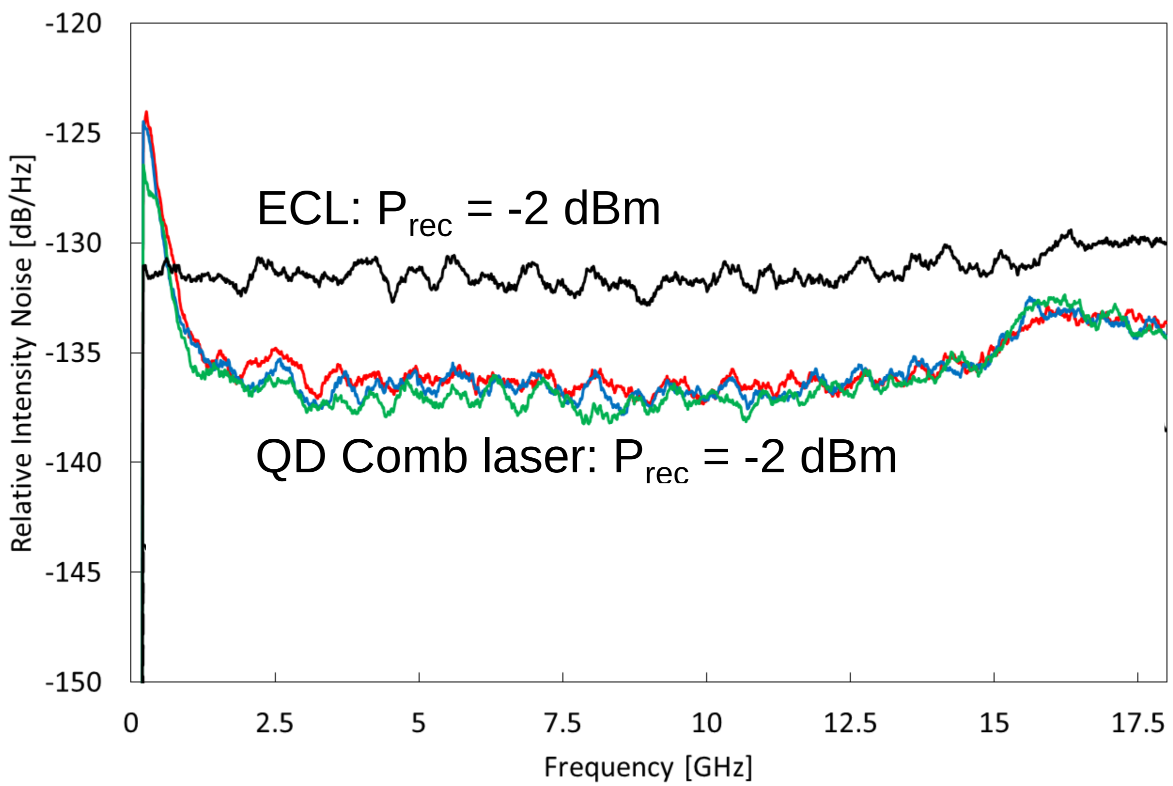
RIN (Comb laser) dominated by low F noise
- Others have seen a similar trend

We also see a hump at 17 GHz
- This is the fundamental FSR (101 GHz/6)
- Perhaps amplitude noise, perhaps not

Relative Intensity Noise – 2/2

Multi-λ laser → amplify → filter out **!one!** λ → measure RIN (for same P_{rec}!)



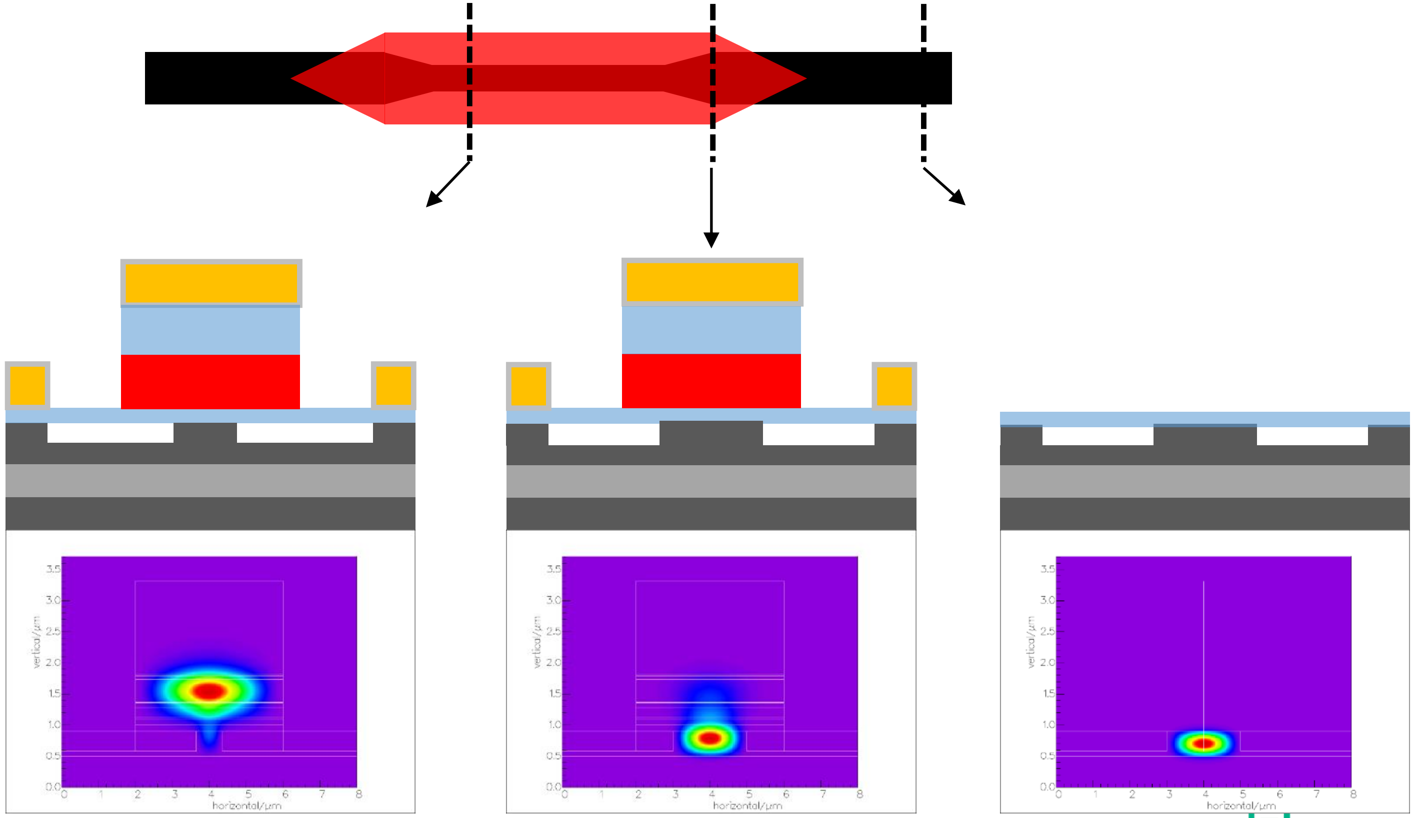


Is comb laser better than ECL?
Probably not.
PDFA sees different input signals
→ different gain/ASE behavior.

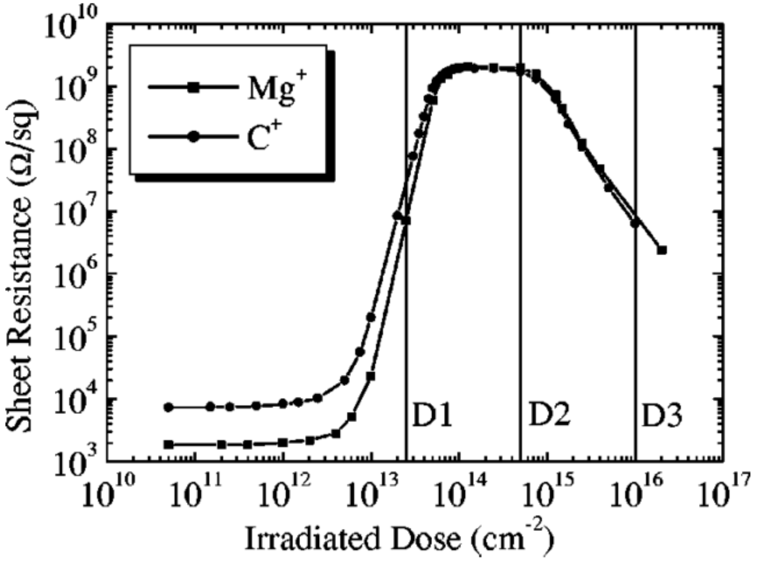
Tapers

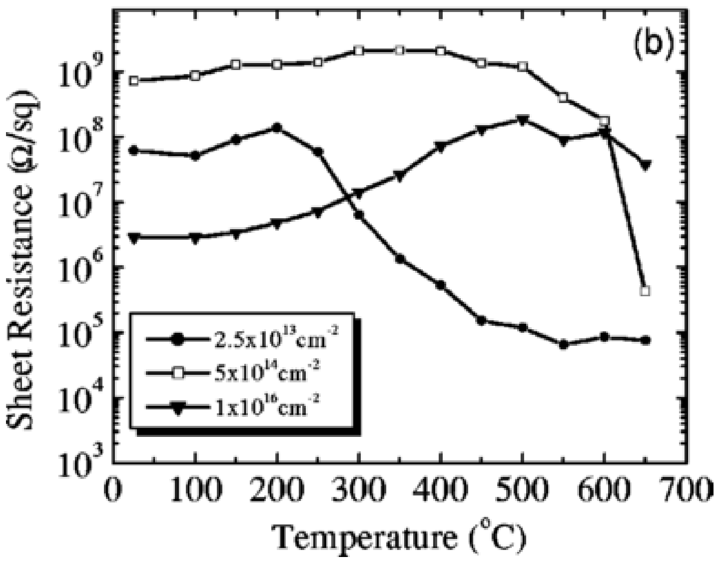
Cross section

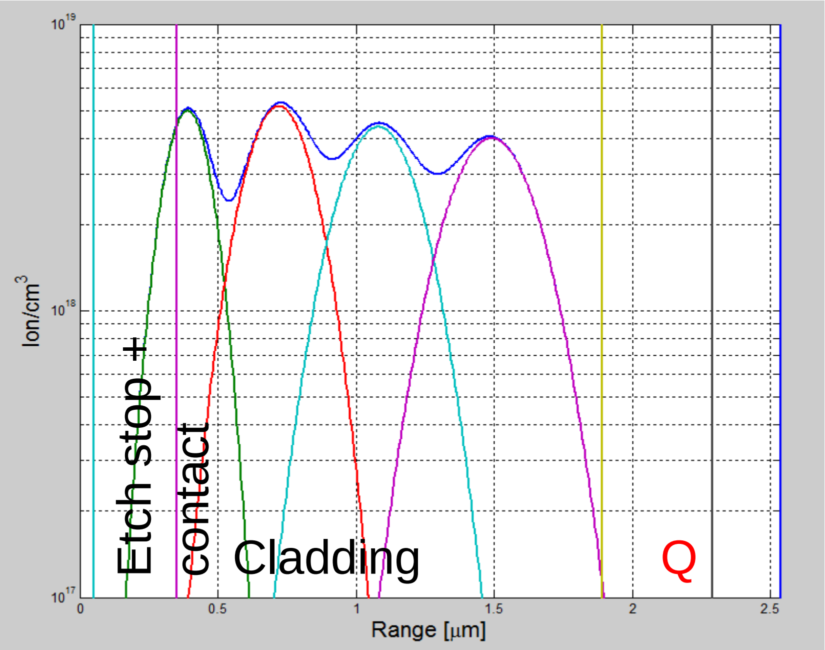
Top down



Implantation



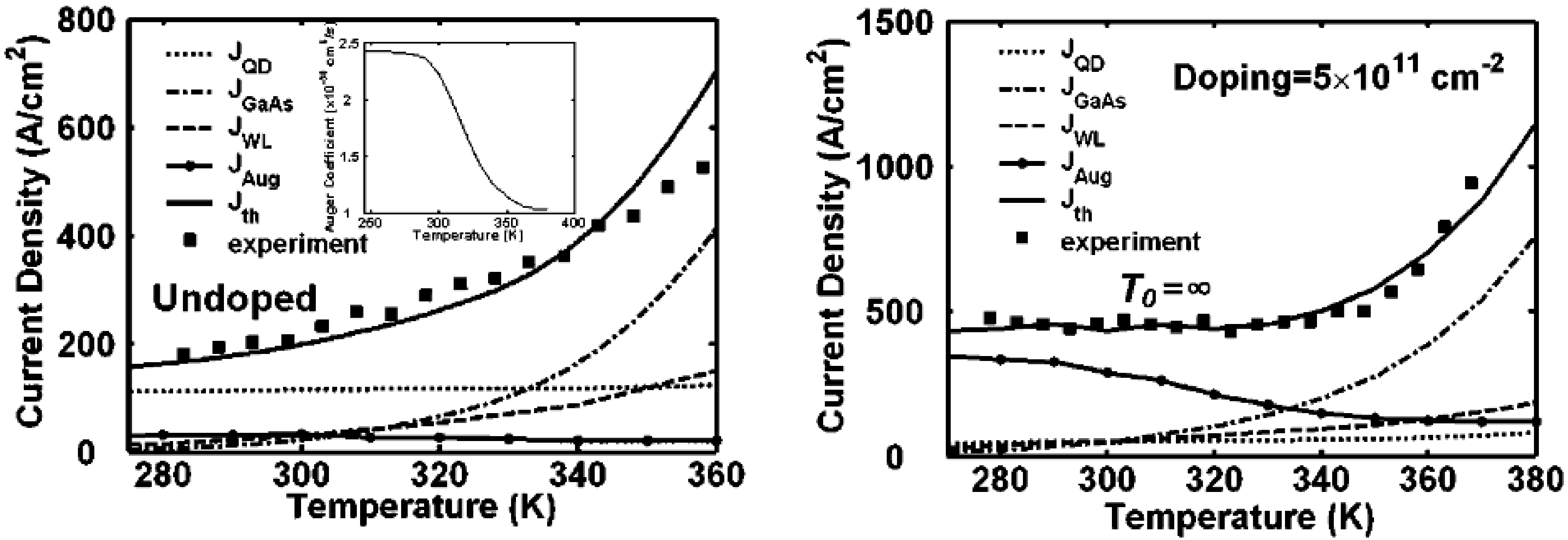




- Target dose in cladding: 1E14 cm^{-2}
- Target concentration in QD: <1E17 cm^{-3}
- Our sample is Be doped, so perhaps some difference in performance

Boudinov et al., “Electrical isolation of p-type GaAs layers by ion irradiation”, JAP, 91, 6585, 2002

P-doping – Auger



- Device with p-doped barriers have larger T_0
- R_{Auger} larger in doped than in undoped devices but R_{Auger} ↓ as Temperature ↑
- Trade T_0 with J_{th} …

P-doping

Doping [acc in QD]	0	6	12	18
Transparency current density [A/cm^2]	45	50	70	75
Threshold current density [A/cm^2]		increases		
Internal loss [cm^{-1}]	2-3	2-4	5-9	12-14
Internal differential efficiency [%]	55	65	75	90
g_{max} [cm^{-1}]	9-15	10-16	16-24	15-25
$f_{3dB\ max}$ [GHz]	1.6	3.8	3.6	5.1
Modulation efficiency [GHz/mA$^{1/2}$]	0.36	0.7	0.73	0.75
dG/di [cm^{-1}/mA]	0.22	0.32	0.39	0.66

Table reproduced from: Alexander et al., "Systematic Study of the Effects of Modulation p-Doping on 1.3-µm Quantum-Dot Lasers", JQE, vol. 43, no. 12, 2007

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We report the first demonstration of a hybrid silicon quantum dot (QD) laser, evanescently coupled to a silicon waveguide. InAs/GaAs QD laser structures with thin AlGaAs lower cladding layers were transferred by direct wafer bonding onto silicon waveguides defining cavities with adiabatic taper structures and distributed Bragg reflectors. The laser operates at temperatures up to 115 °C under pulsed current conditions, with a characteristic temperature T_0 of 303 K near room temperature. Furthermore, by reducing the width of the GaAs/AlGaAs mesa down to 8 μm, continuous-wave operation is realized at 25 °C.


100%
1x2
MMI
SOA SA SOA
50%
2x2
MMI
R~10%