Development of 1550nm InAs on InP emitting QD Lasers

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TECHNION Israel Institute of Technology

CEP Computational Electronics & Photonics

Mellanox TECHNOLOGIES

NVIDIA

INA

CINSaT Center for Interdisciplinary Nanostructure Science and Technology

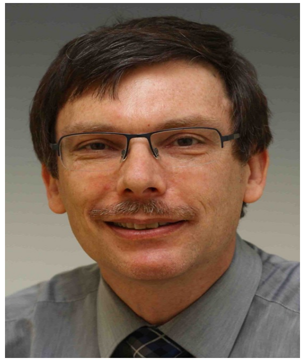
U N I K A S S E L
V E R S I T Ä T

Involved People

1.5 µm InP Based QD lasers

Vitalii Sichkovskyi, J.P. Reithmaier

- S. Banyoudeh, A. Abdollahinia (high-speed lasers)
- Annette Becker (narrow linewidth lasers)
- Florian Schnabel, Anna Rippien (processing)


Further Cooperations

- **Technion: Gadi Eisenstein**, Ori Eyal, Tali Septon, Sutapa Gosh, (➞ High-speed QD lasers, QD-SOAs, narrow-linewidth lasers)
- **Kassel Univ.: Bernd Witzigmann**, Marco Bjelica (CEP)

- **TU Wroclaw: Grzegorz Sek et al.**
- **Nvidia/Mellanox: Isabelle Cestier, Elad Mentovitch**

Wrocław University of Technology — CEP Computational Electronics & Photonics — TECHNION Israel Institute of Technology — Mellanox Technologies — NVIDIA

Outline

Low-Dimensional Gain Material and Impact on Device Properties

InP-based QD Lasers

High-Temperature Stable QD Lasers

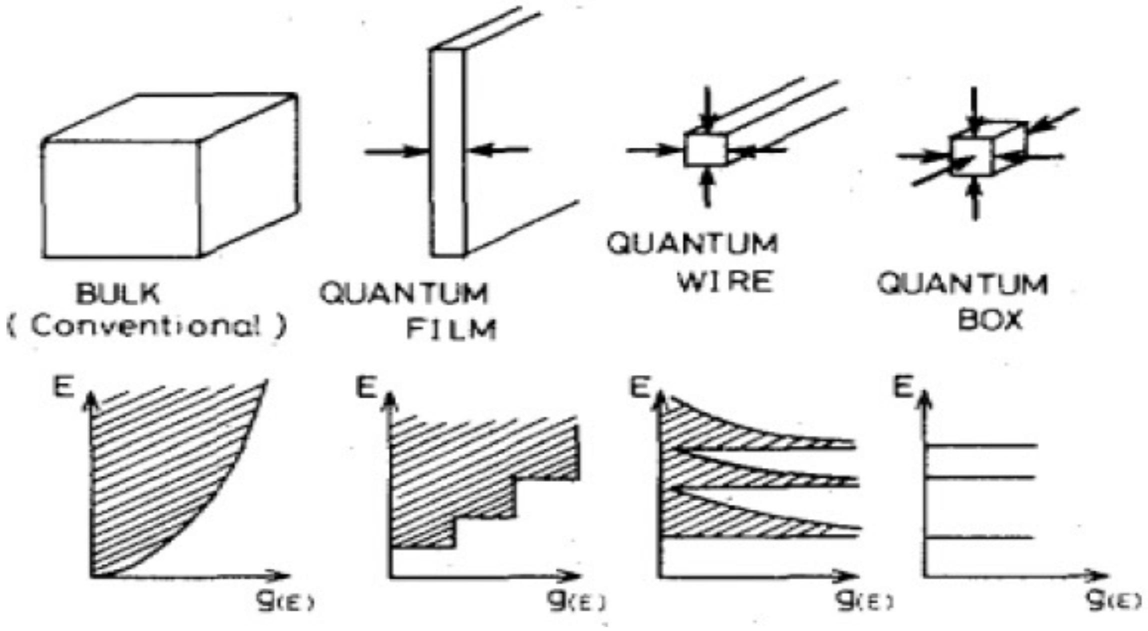
Narrow-Linewidth QD-DFB-Lasers

Outlook (Extended wavelength range)

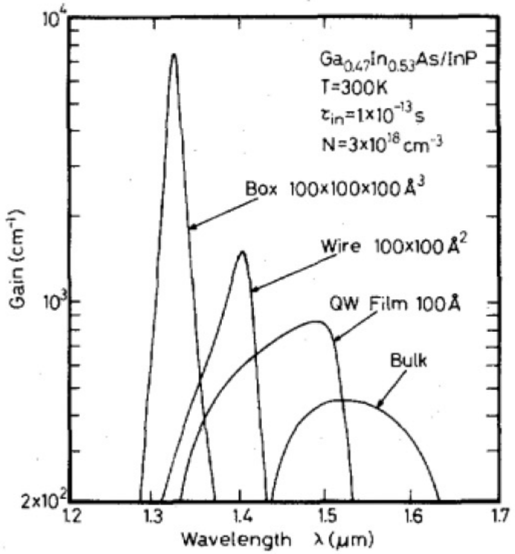
Summary

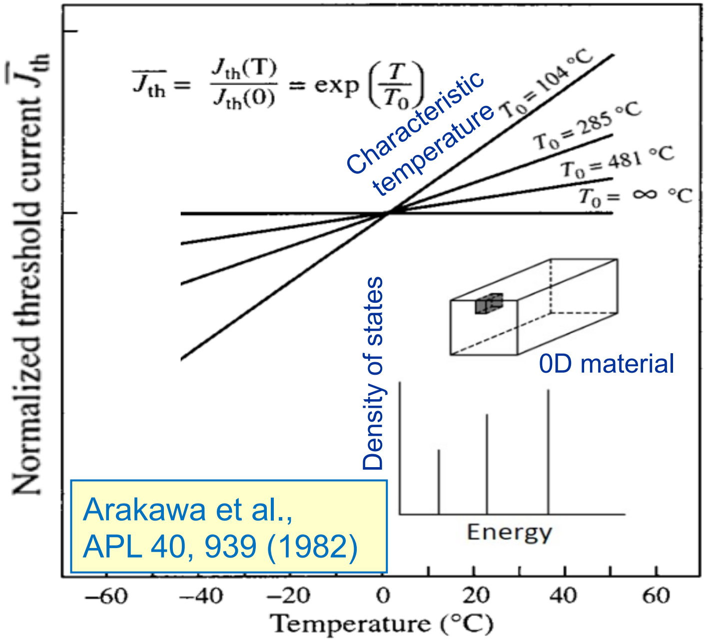
Low-Dimensional Gain Material and Impact on Device Properties

Material gain of low-dimensional material



Asada et al., IEEE JQE 22, 1915 (1986)





$$\overline{J_{th}} = \frac{J_{th}(T)}{J_{th}(0)} = \exp\left(\frac{T}{T_0}\right)$$

Arakawa et al.,
APL 40, 939 (1982)

Major statement:

- 10 times higher gain than in QWs
- in ideal case no temperature dependence

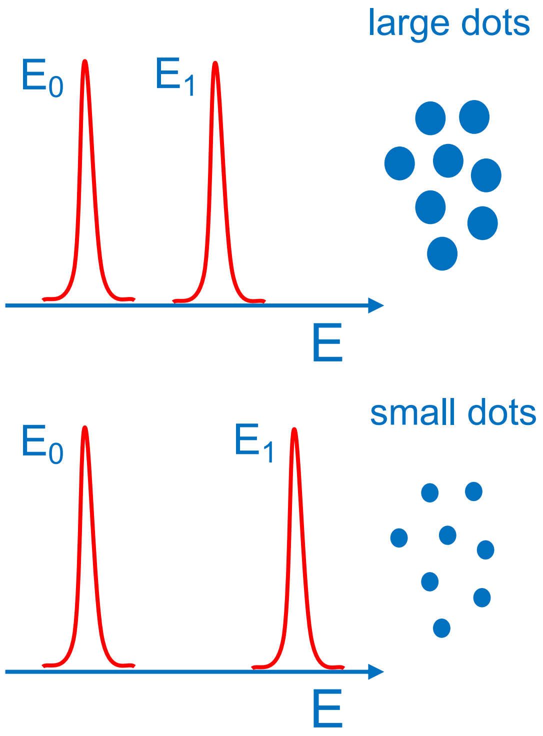
→ Only applicable in case of
- small size distribution (atom-like),
- high QD density (high modal gain)
- and large level splitting (>> kT)

Engineering of Optical Gain by QD Material

Three main parameters

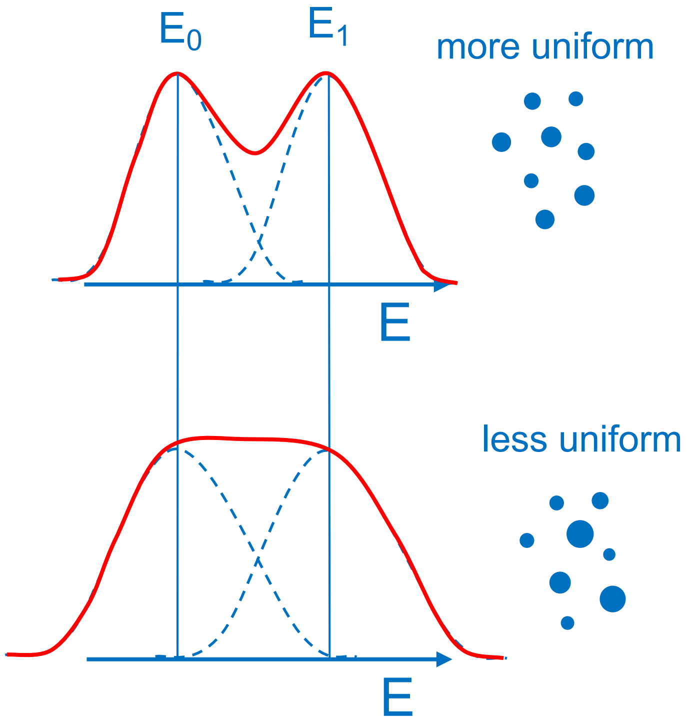
Dot size:

→ level splitting



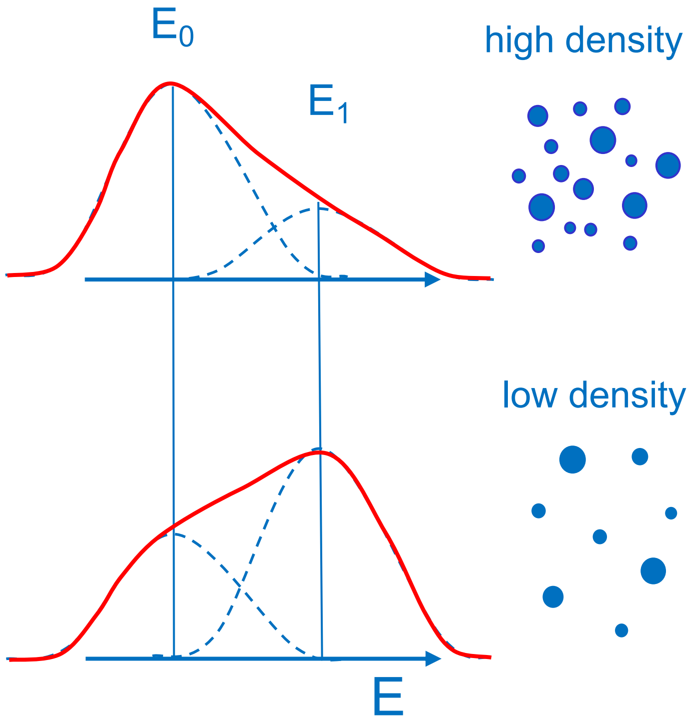
Size distribution:

→ gain flatness



Dot density:

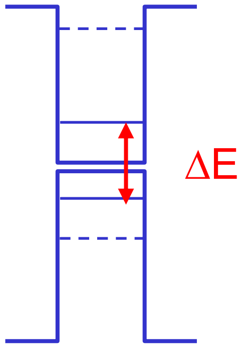
→ gain saturation



Advantages of atom-like gain material

Static Properties

- Very high temperature stability
- Zero threshold and low power consumption
- Very narrow linewidth (α, R'_{sp})



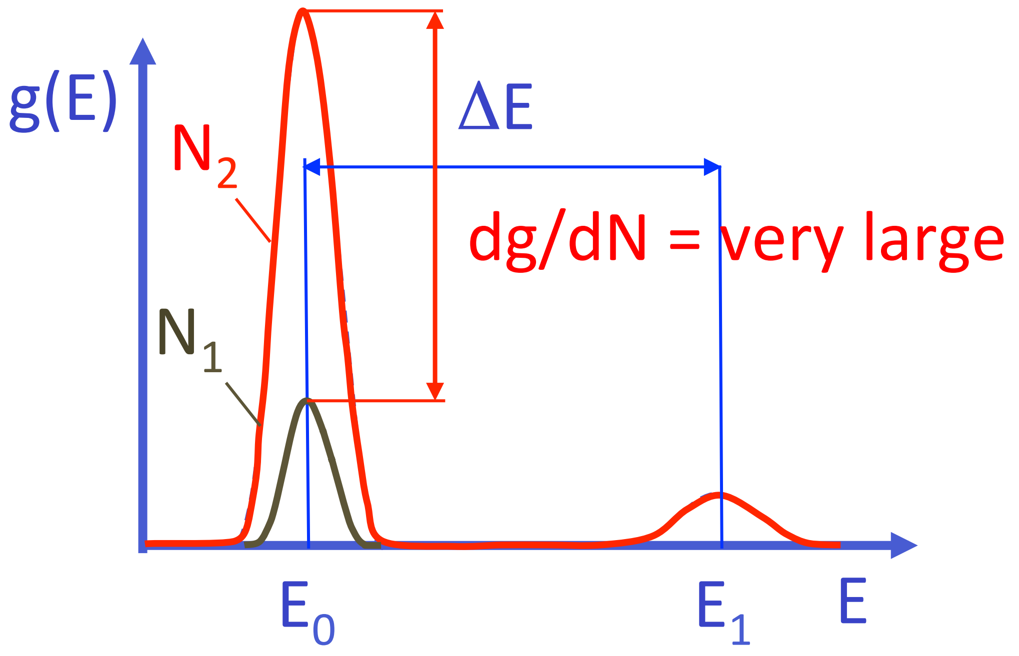
Laser Linewidth

$$\Delta\nu = \frac{\Gamma R'_{sp}}{4\pi N_P}\left(1+\alpha^2\right)$$

$$\alpha = -\frac{4\pi}{\lambda}\frac{dn/dN}{dg/dN}$$

Dynamic Properties

- Very high differential gain a = dg/dN
- Zero chirp ($\alpha = 0$)



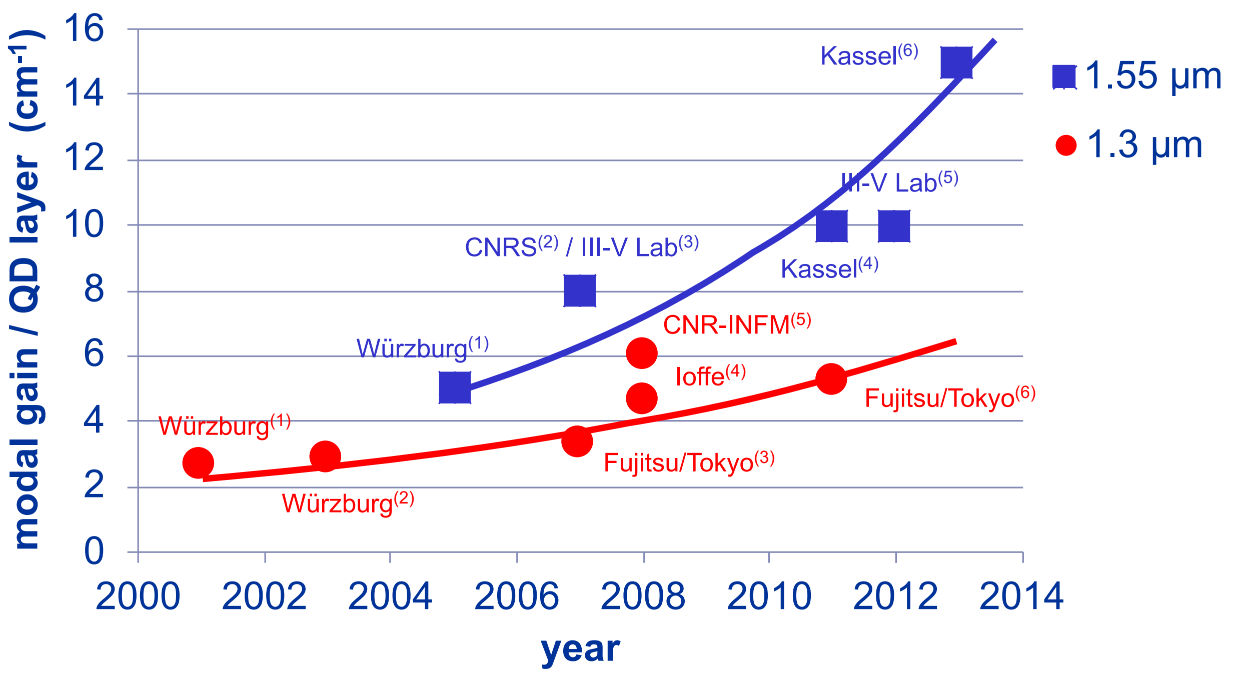
Resonance Frequency

$$\omega_R \propto \sqrt{a \cdot \frac{N_p}{\tau_p}}$$

Why InP-based 1.3 µm QD Lasers?

Usually, 1.3 µm QD lasers based on GaAs

InP-based QD lasers
→ Modal gain typically by a factor of 3 higher
→ Allow short cavity devices (<< 1 mm)



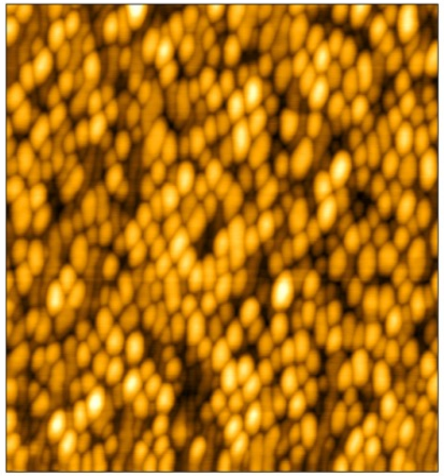
Additional advantages of InP-based QD lasers

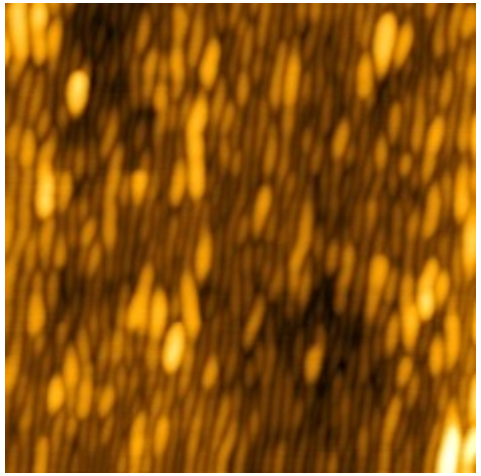
- Much less strained QDs (InP: 3.2 % / GaAs: 7.2%)
  → Improved reliability expected
- Larger wavelength variability (> 100 nm gain range possible)
- Tensile strained barriers possible for strain compensation

InP-based QD Lasers

QD Formation on InP-based Compound Surfaces

As_2 growth mode



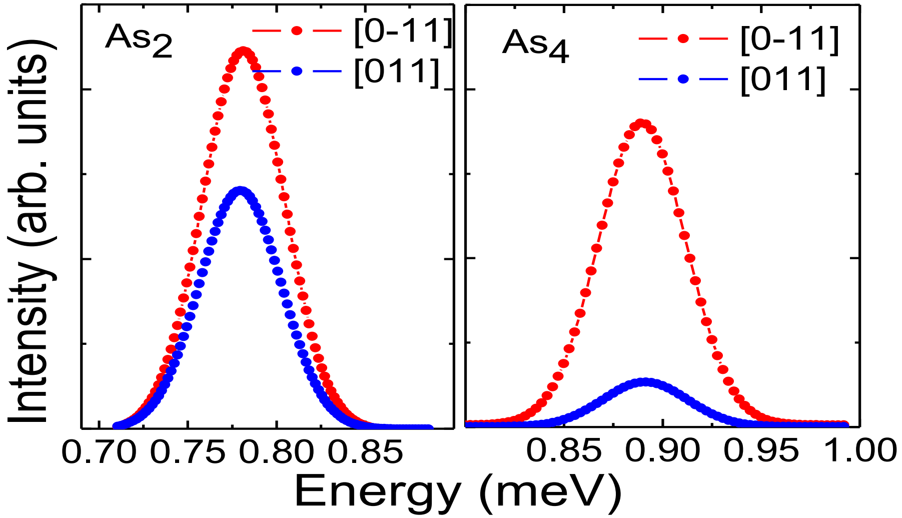


As_4 growth mode

C. Gilfert et. al., *APL* **96**, 191903 (2010)

➡ Quantum dots are formed only by supplying As_2 during InAs deposition

Polarization

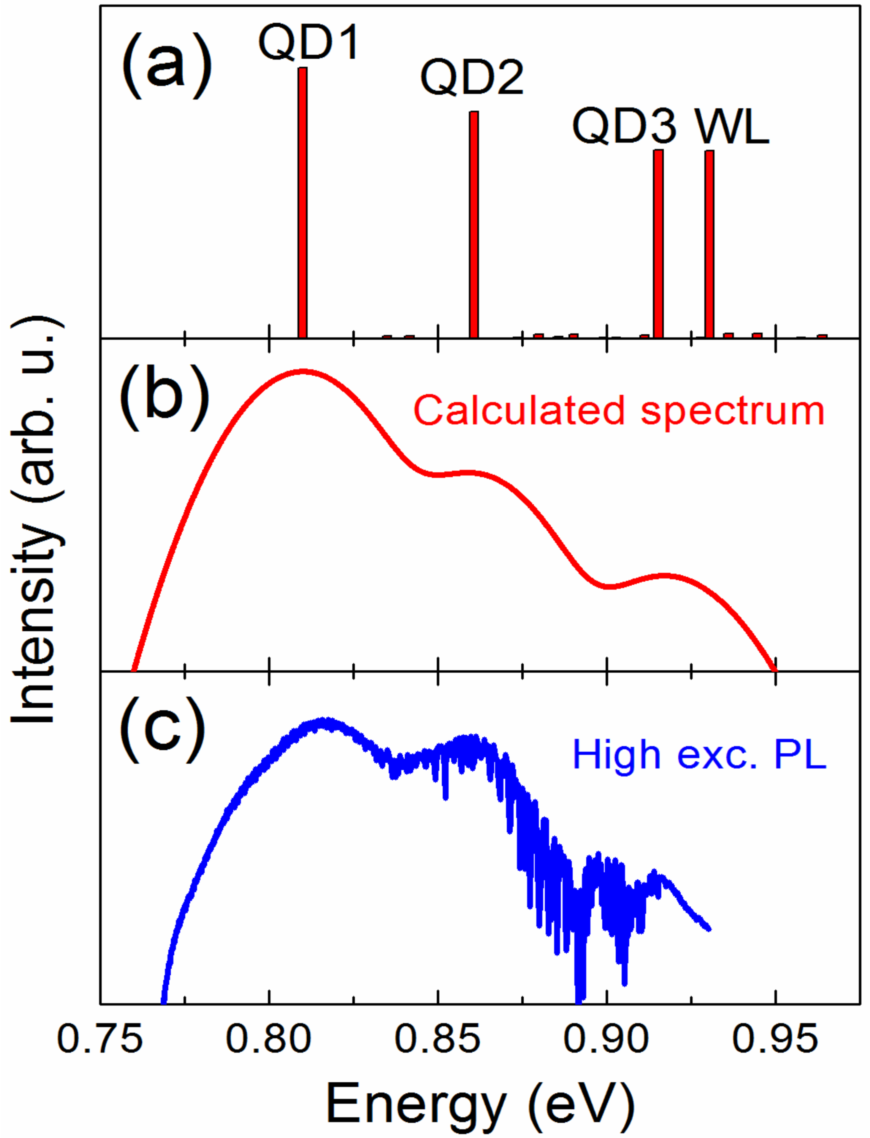


Quantum State Calculations and Verification

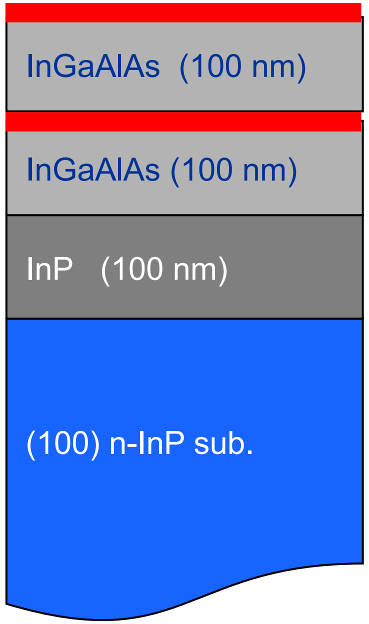
- Electron and hole state calculations using multi-band k • p theory
- Clear identification of QD-like behavior with confined excited states
- Verification by high-power excitation photoluminescence

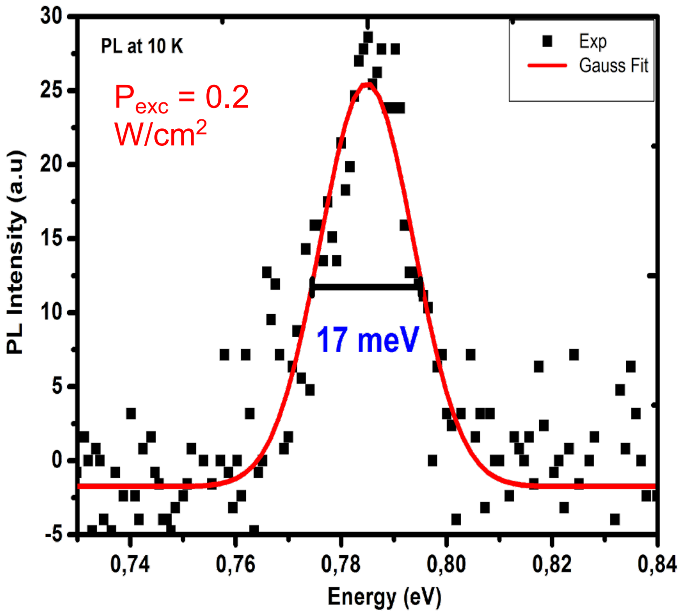
Wrocław University of Technology

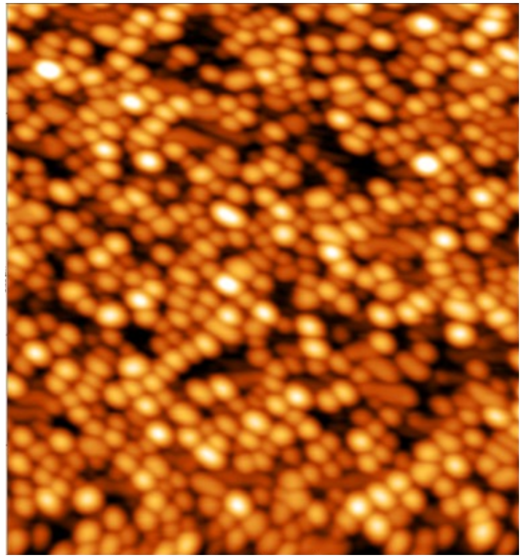
*A. Marynski et. al., JAP **114**, 094306 (2013)*



Quantum dot material





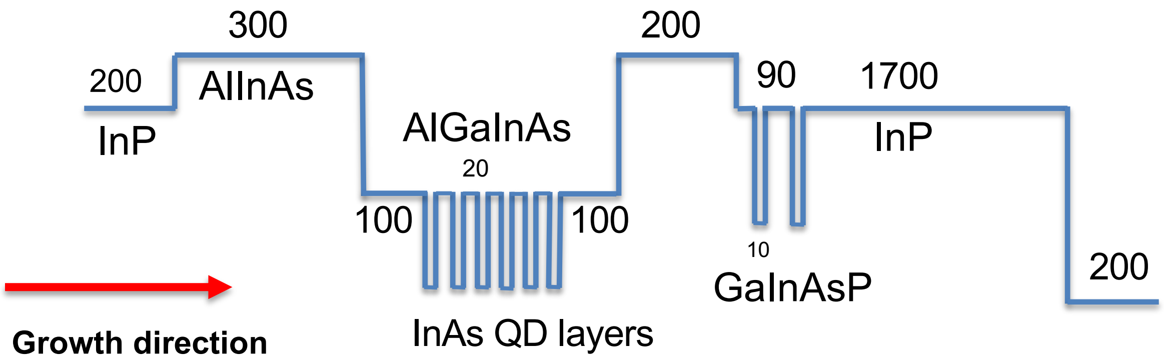


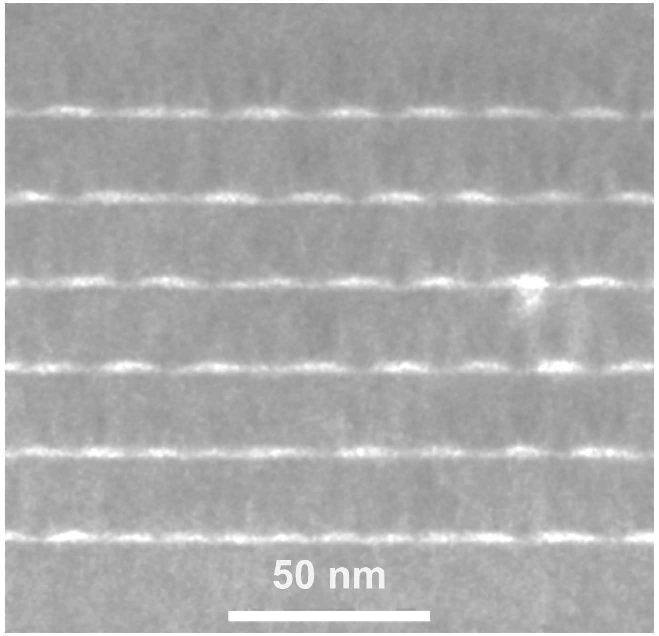
1 x 1 μm²

- nearly circular shaped QDs of high dot densities (5-6 x 10^{10} cm^{-2})
- Single QD layer with very small size variations
- Record linewidth of 17 meV for single QD layer

S. Banyoudeh et al., JCG 425, 299 (2015)

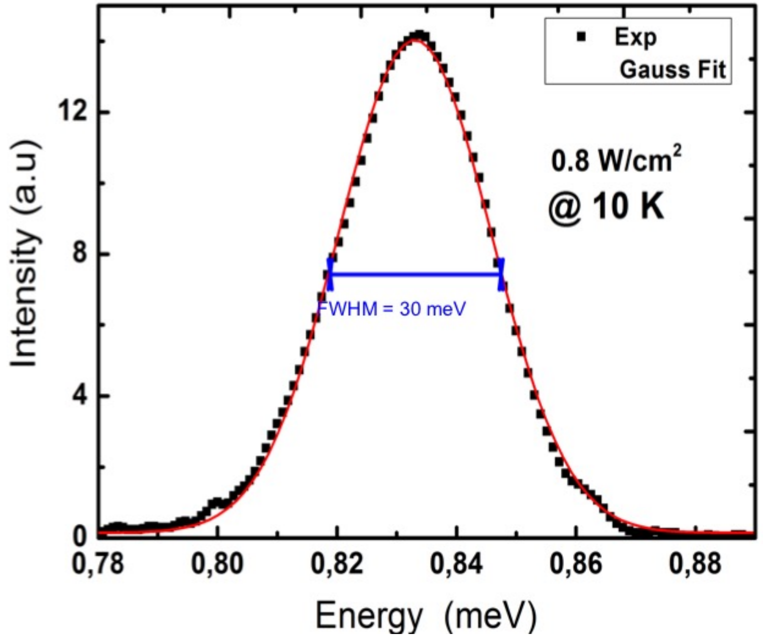
Layer design of high-speed QD lasers





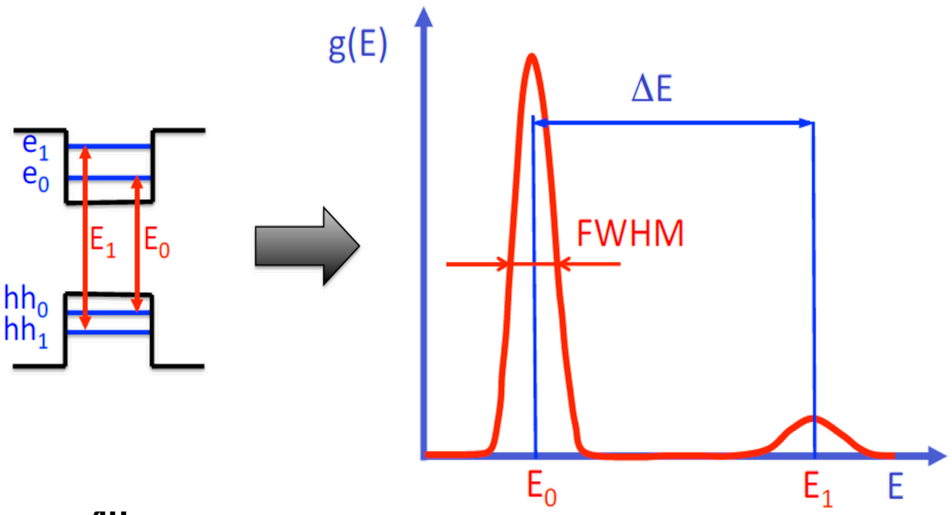
A. Rosenauer

Universität Bremen

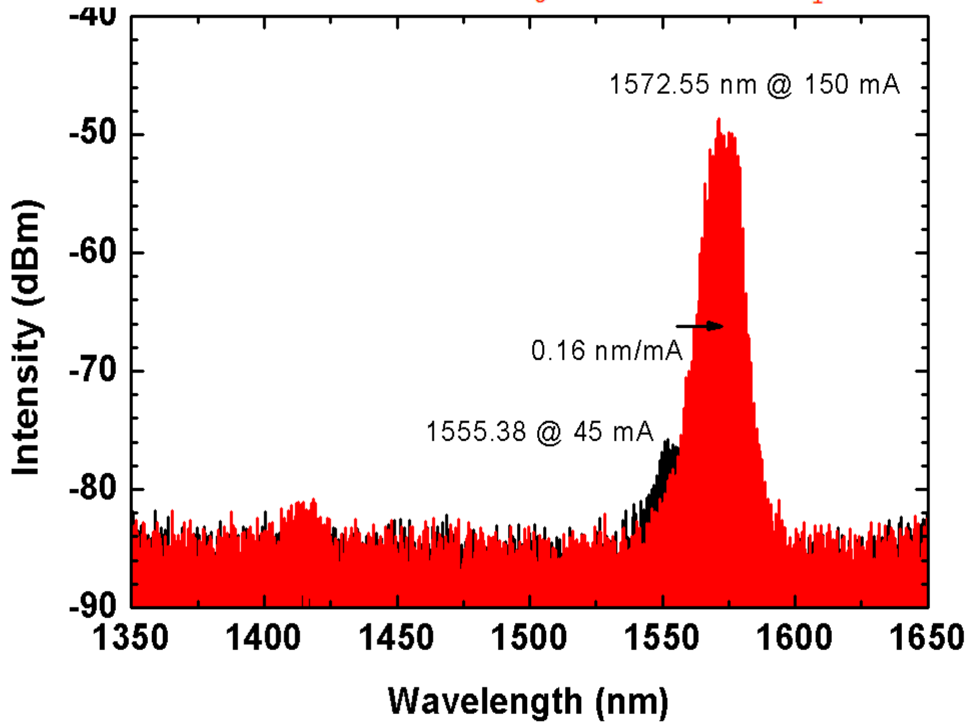


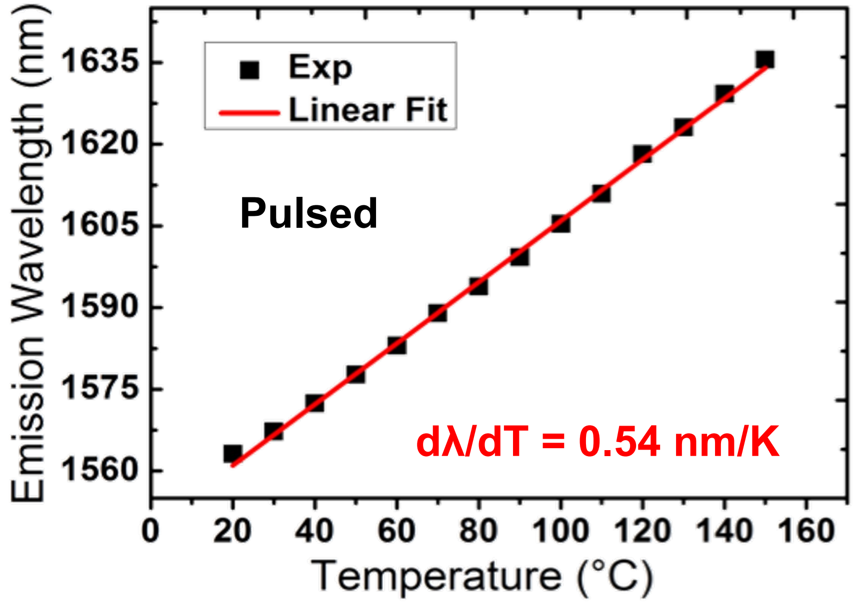
- Laser design with 6 QD layers and high optical confinement
- Narrow ensemble linewidth for 6 stacked QD layers with FWHM = 30 meV

Fundamental Properties of QD Lasers



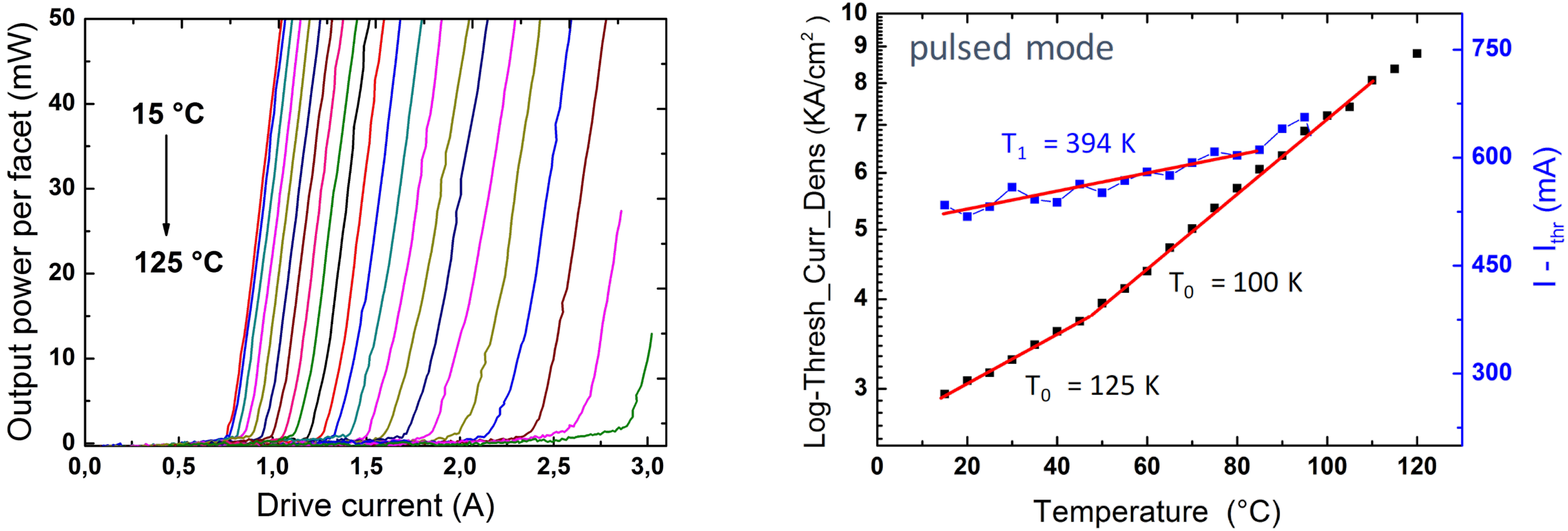
- Atomic-like gain function
- Symmetric ground state gain
- Stable ground state gain at any operation condition





High-Temperature Stable QD Lasers

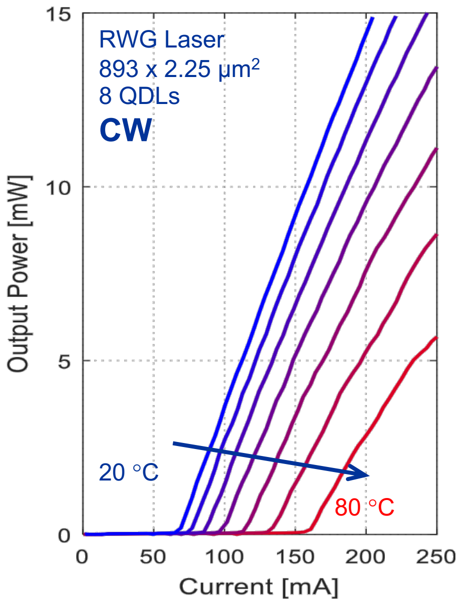
Characteristic temperatures in broad area lasers

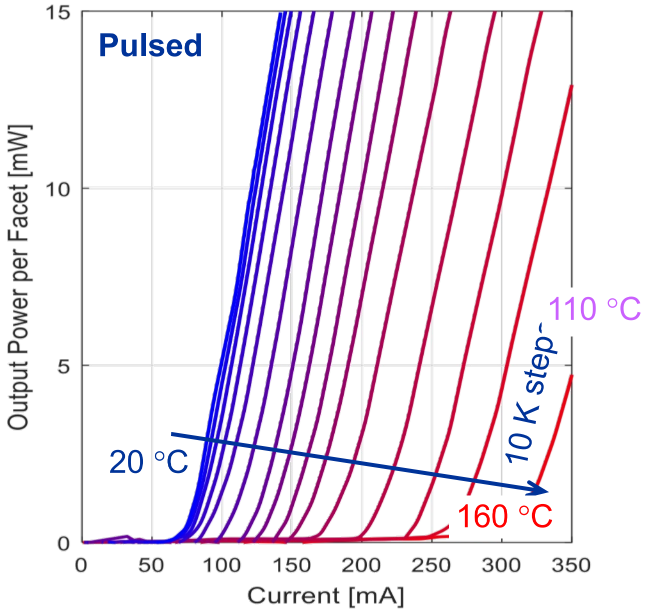


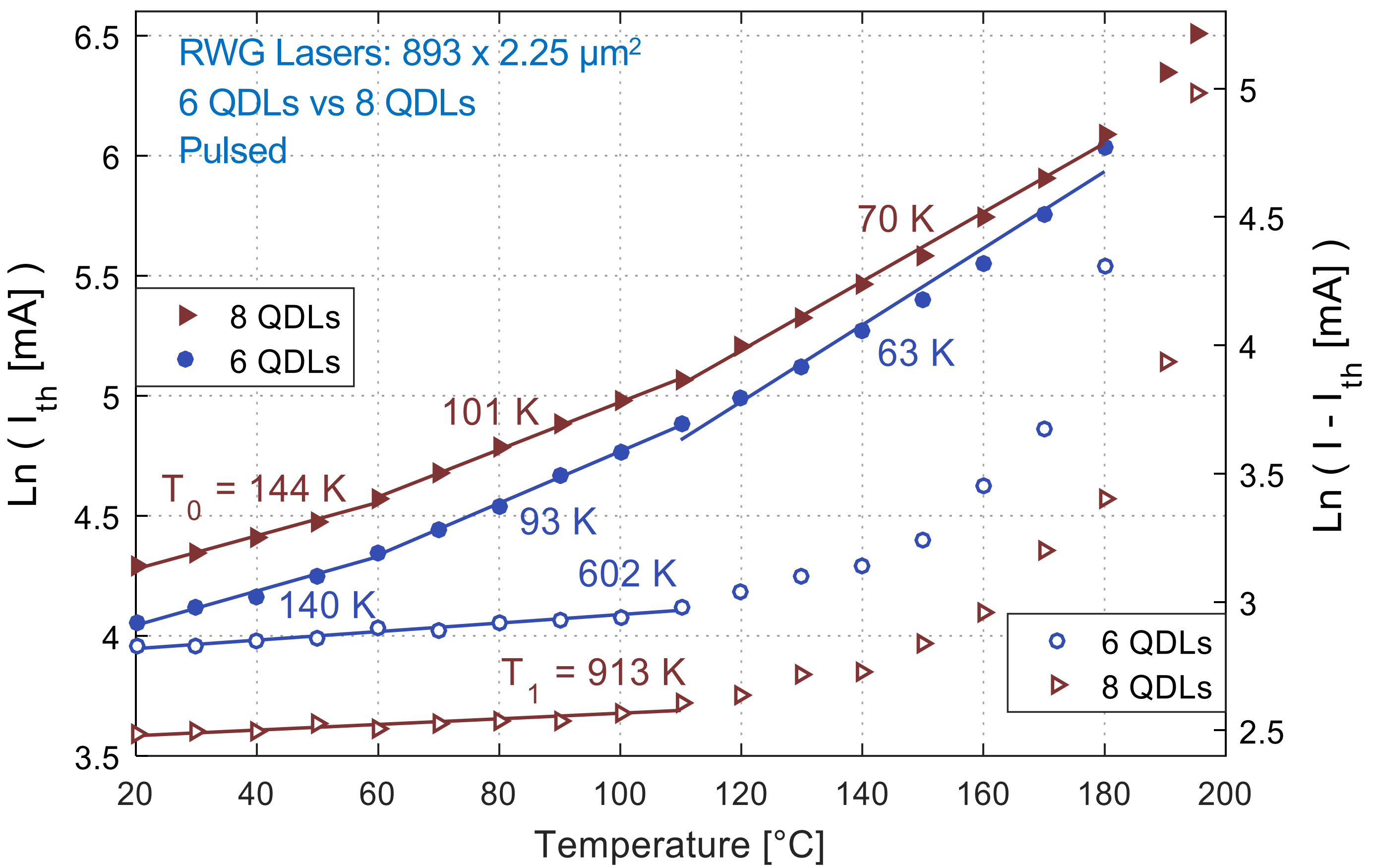
- Broad area lasers with 100 µm stripe width and 292 µm cavity length
- Nearly constant slope efficiency from 15 – 125 °C
- High characteristic temperature T_0 of 125 K (45 °C), > 100 K (above)
- High output power stability with T_1 of 394 K (@80 mW, 15 to 95 °C)

S. Banyoudeh et al., Phot. West, Proc. 9767-0I (2016)

Impact of epitaxial design on temperature stability



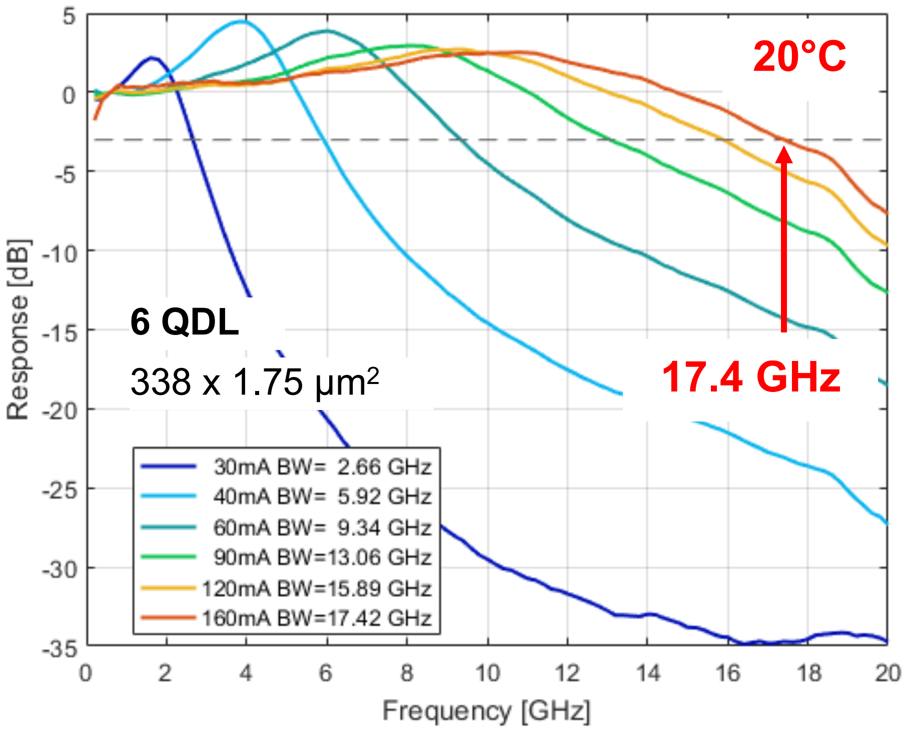


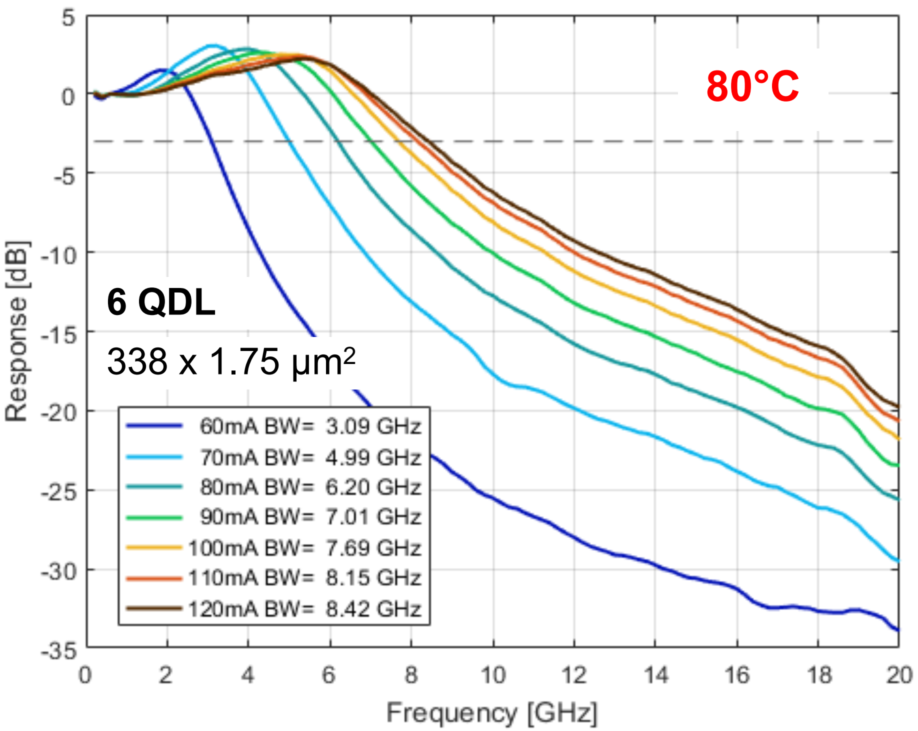


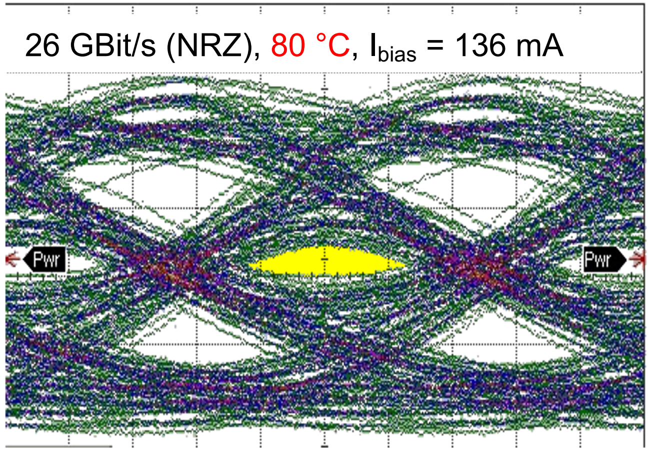
- T_0 > 140 K (20 – 60 °C) and > 100 (up to 110 °C)
- higher temperature stability with lasers of 8 QD layers

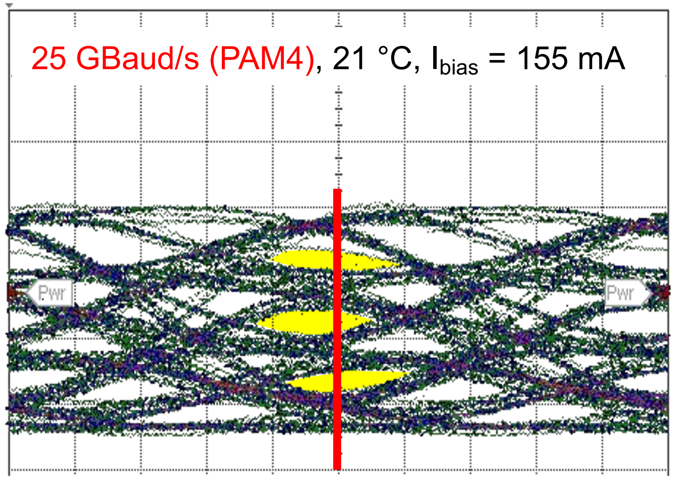
A.. Abdollahinia et al., Optics Express 26, 6056 (2018)

Small-Signal Modulation Response









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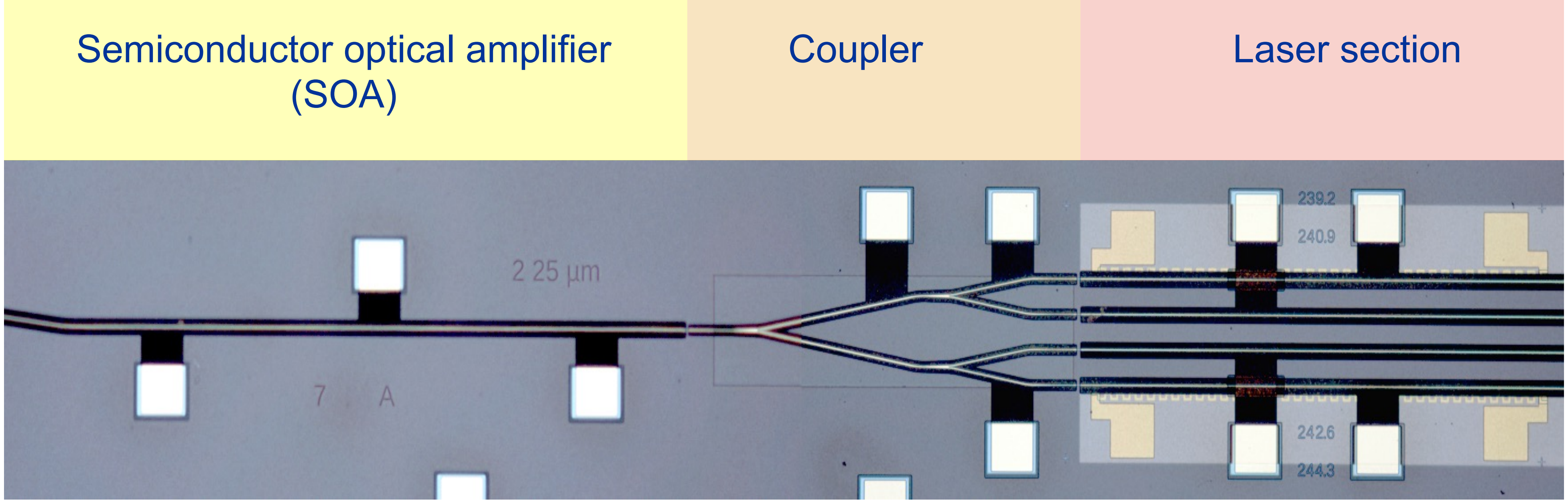
A. Abdollahinia et al., Optics Express 26, 6056 (2018)

S. Bauer et al., IEEE Nano-technology Magazine 23 (2021)

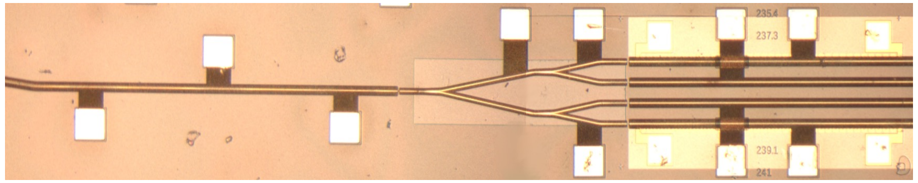
Narrow-Linewidth QD-DFB-Lasers

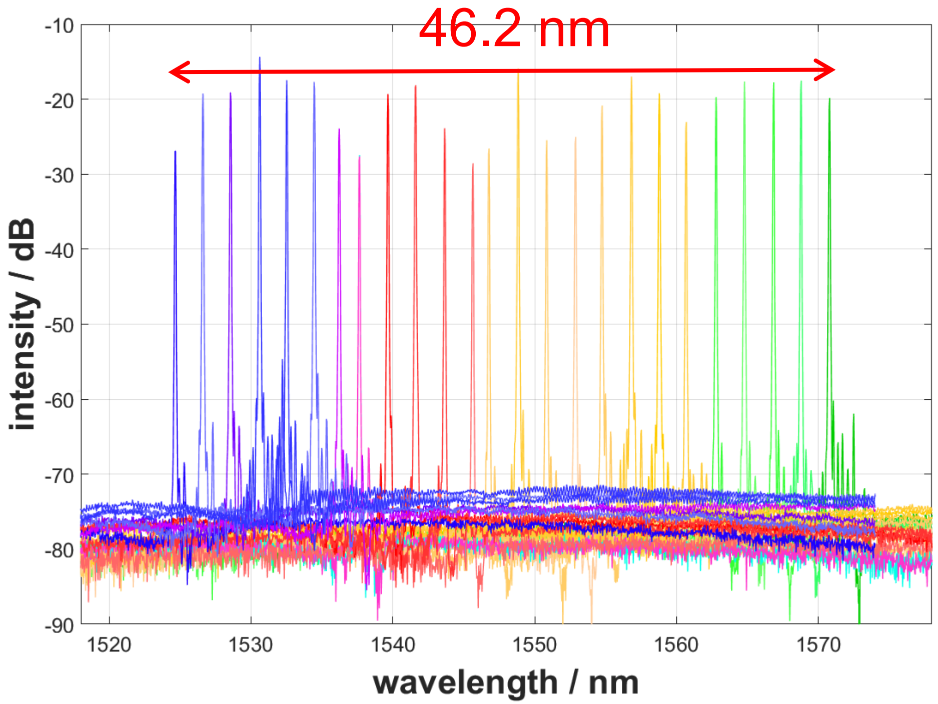
Motivation

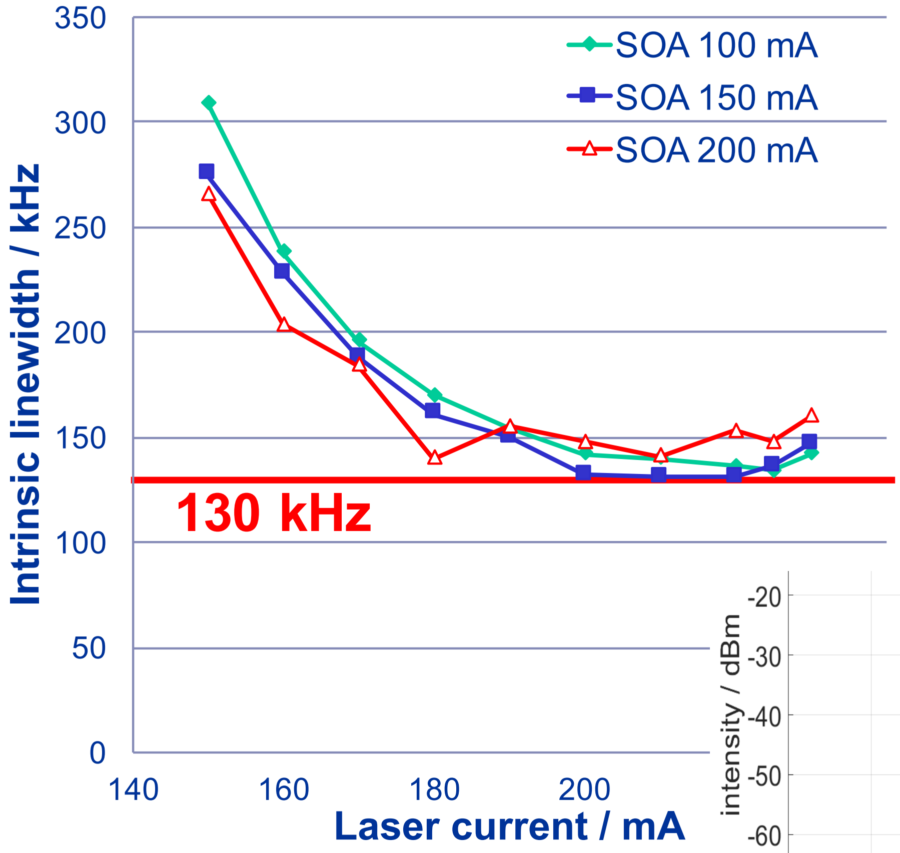
- **Local oscillators for coherent communication need narrow linewidth and broadband tunability**
  - Linewidth reduction by using QD material
  - Expanding tuning range to > 40 nm by using arrayed lasers
  - Adjusting output power by using broadband SOA

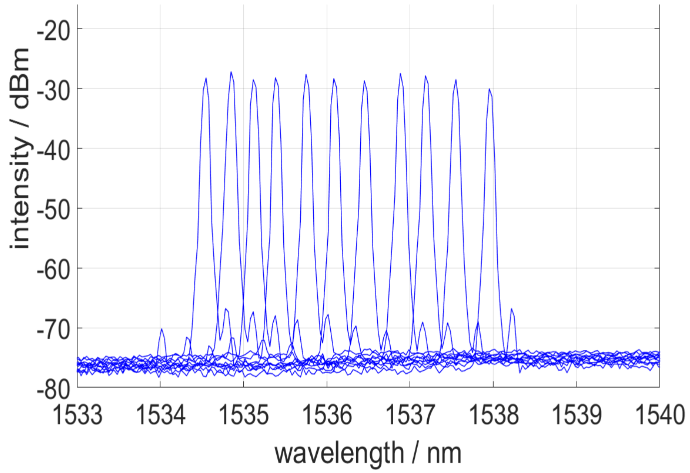


New generation of tunable narrow linewidth source









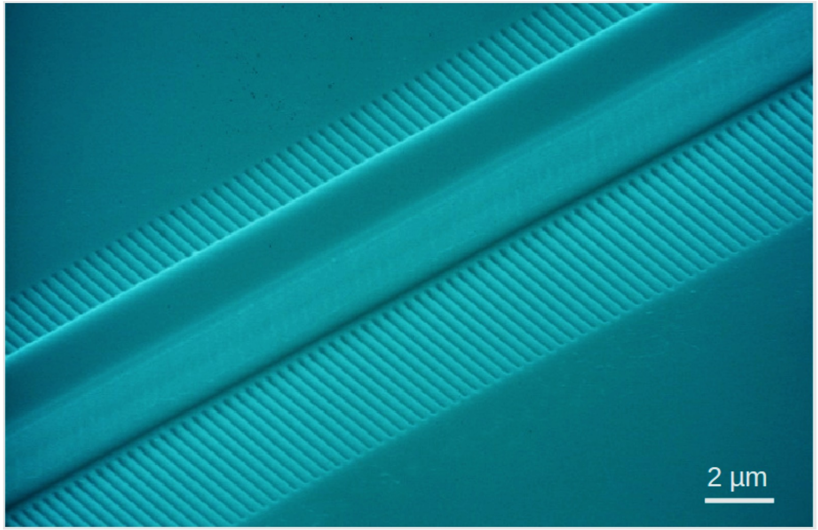
- Mounted chip, laser facet HR, SOA facet AR coated
- Wide tuning range (whole C+ band)

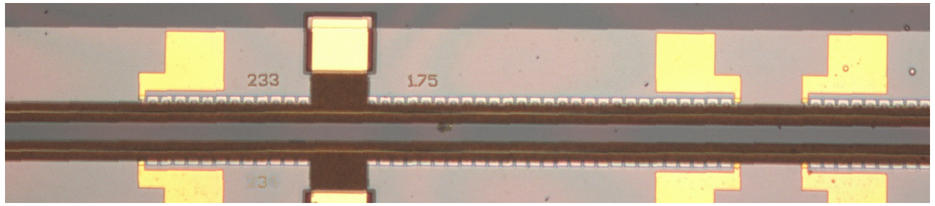
- 130 kHz from SOA facet

→ The amplification does not deteriorate the linewidth

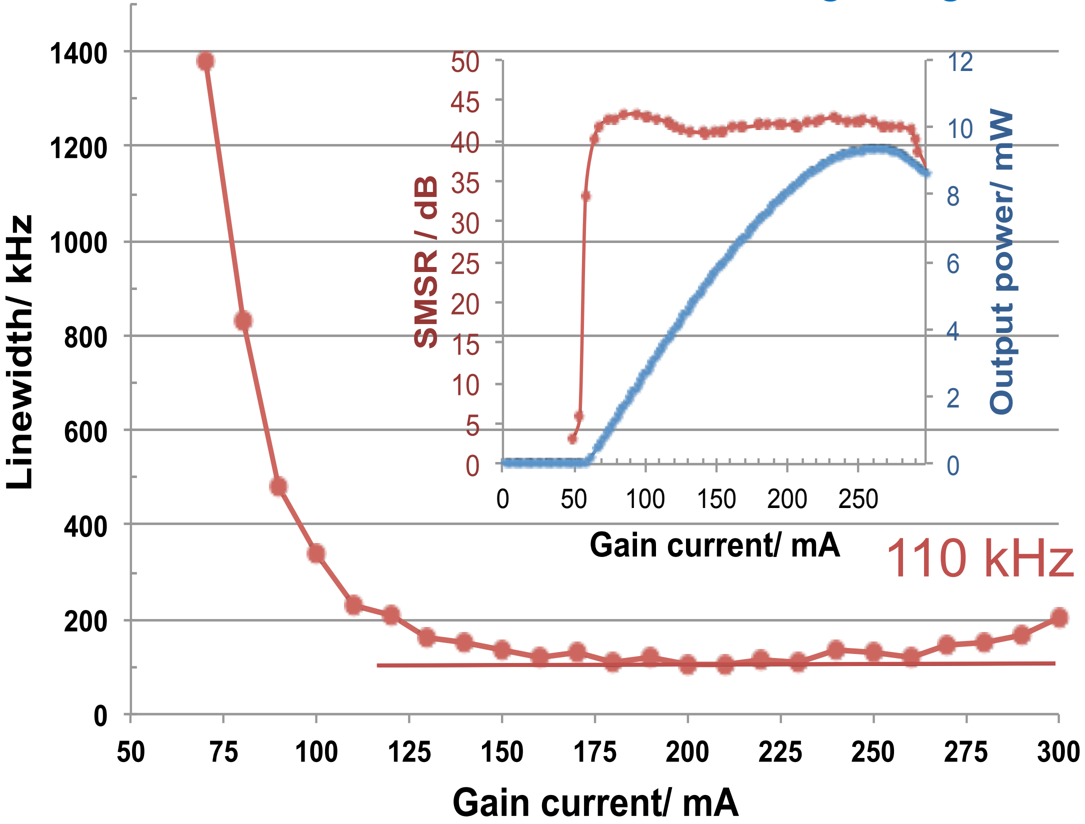
A. Becker et al., ISLC, Kobe (Sept. 2016)

Emission linewidth of single QD DFB laser





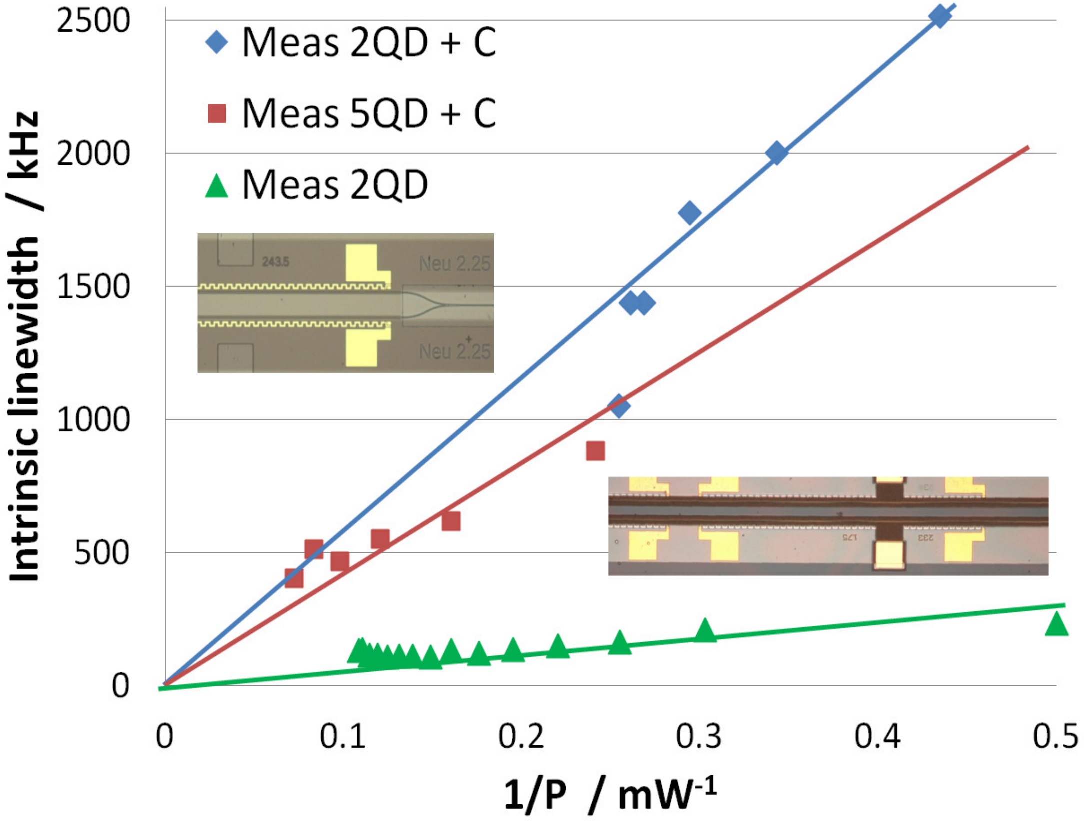
About 1.2 mm long QD DFB laser with two cleaved facets and 1st order lateral gratings



- 2 QD layer design
- QD DFB laser cleaved from monolithic chip show stable SMSR and > 9 mW/facet
- Linewidth of 110 kHz obtained nearly power independent between 4 – 9 mW/facet

A. Becker et al., Phot. West, Proc. 9767-0Q (2016)

Impact of QD material and laser design/operation

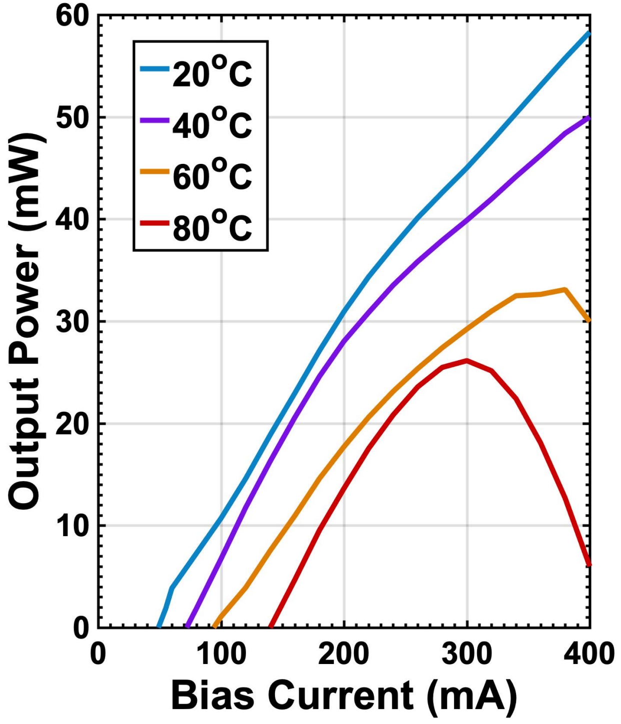


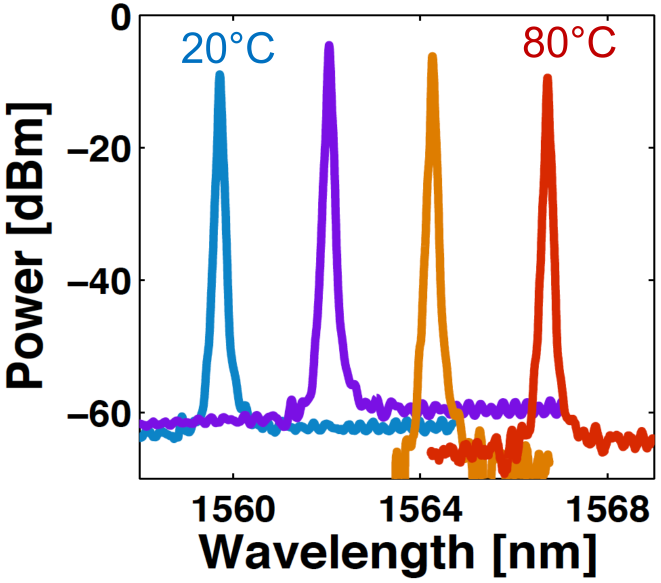
$\Delta\nu \sim (1+\alpha^2)/P$

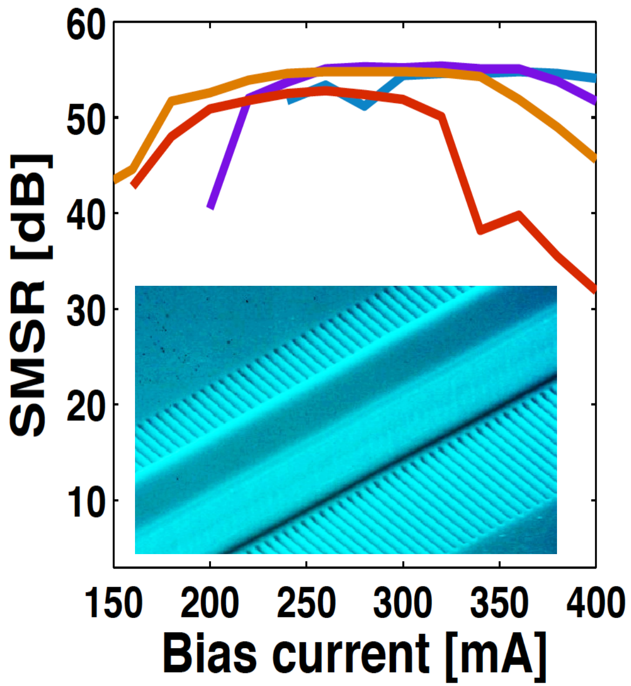
A. Becker et al., Appl. Phys. Lett. 110, 181103 (2017)

- Linewidths of devices of different numbers of QD layers with & without couplers
- Values close to threshold and for very high currents are not considered
- The fitted lines clearly show a linear increase of the linewidth with inverse output power as theoretically expected

QD-DFB-Laser with 5 QD layers





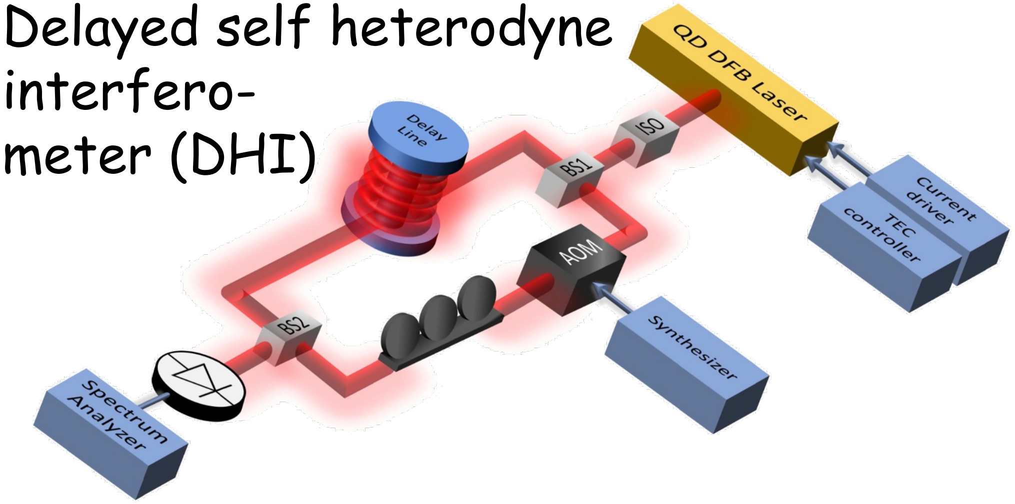


- QD-DFB lasers with 5 QD layers (2 µm ridge, 1.5 mm length, AR/HR coating)
- 1st order DFB gratings (240 nm) with $\lambda/4$ phase shift distributed in 3 steps
- High single mode output power of > 58 mW (@20 °C) and 26 mW (@80 °C)
- High SMSR (> 50 dB) over a wide bias current range and operation temperature

T. Septon et al., PW, Novel In-Plane ..., Monday [10939-5]
T. Septon, A. Becker et al., OFC, San José (March 2019)

Linewidth Comparison between DHI and OFC beat

Delayed self heterodyne interfero-meter (DHI)



Beating with optical frequency comb (OFC)

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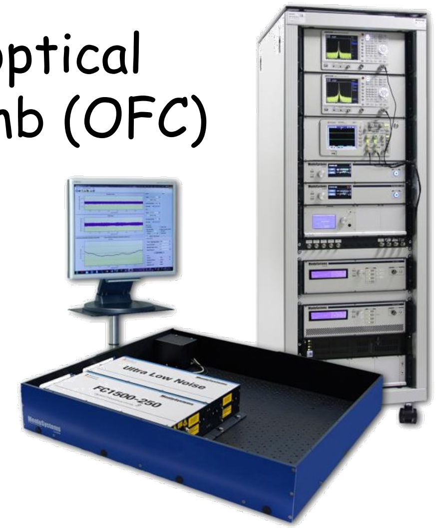
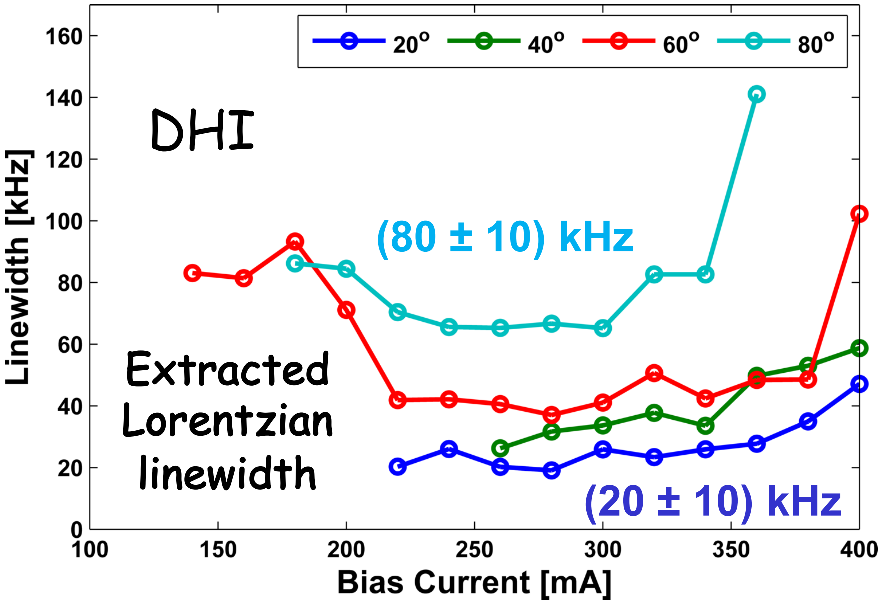
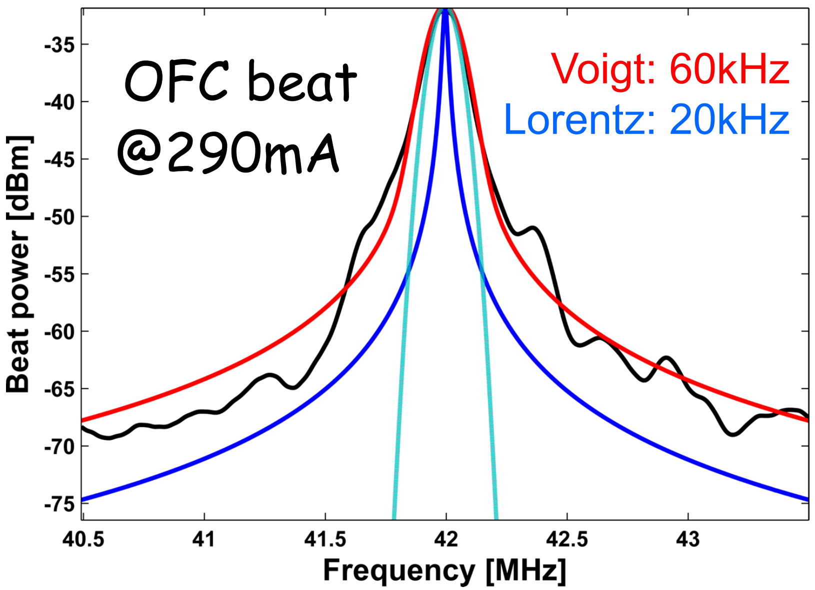
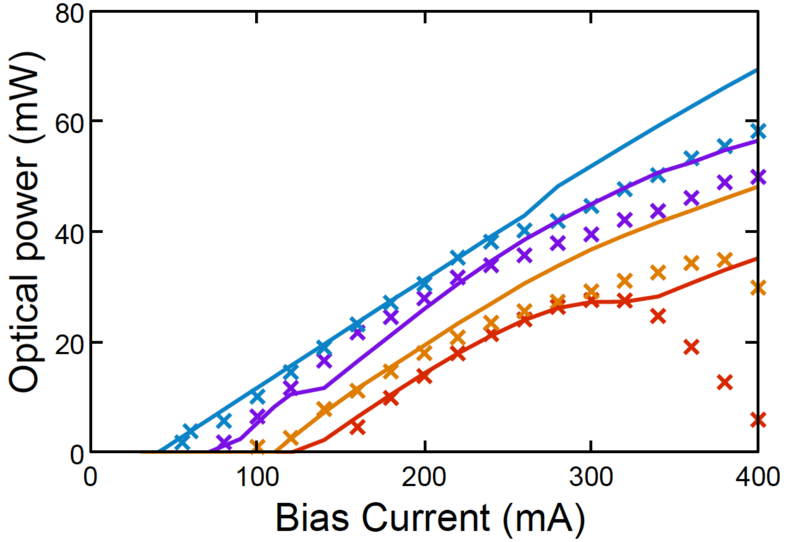






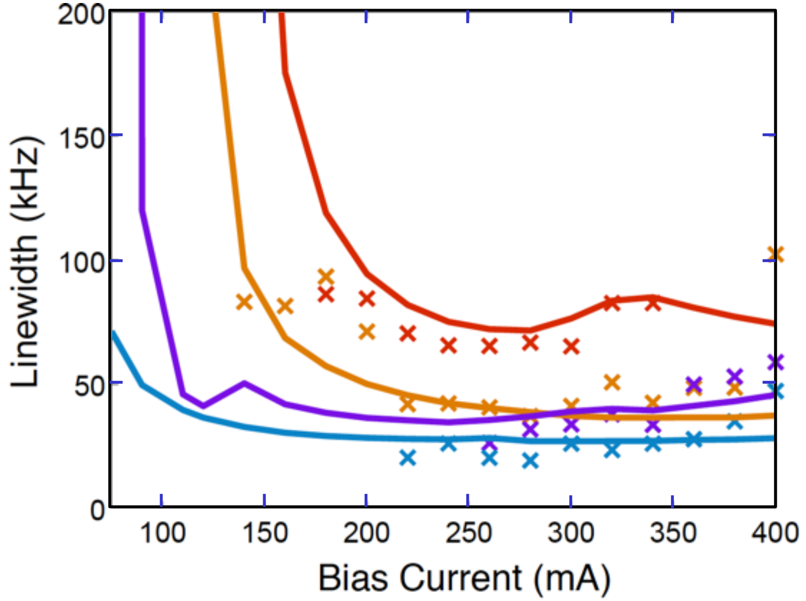
T. Septon, A. Becker et al., ISLC, Santa Fe (2018)

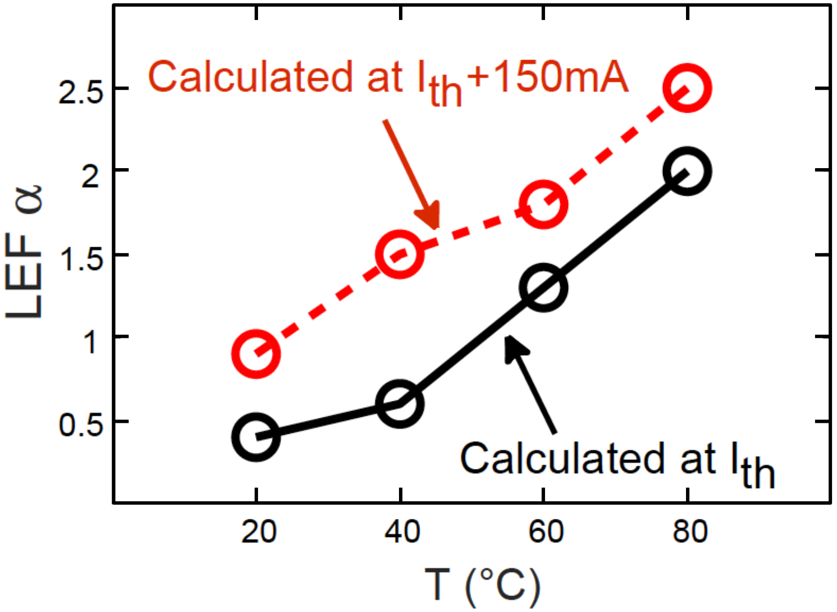
Theory & Linewidth Enhancement Factor



- Advanced theory including temperature and current dependent α-factor
- Can be well fitted to P-I curves and linewidths

CEP Computational Electronics & Photonics





- T and I dependent α-factor can be extracted with 0.4 at 20 °C

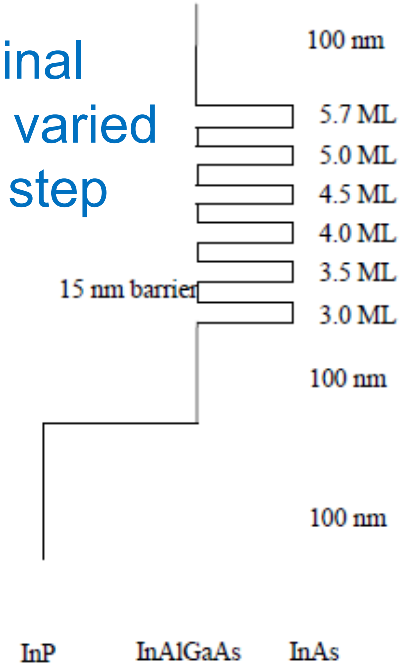
T. Septon et al., Optica 6, 1071 (2019)

Outlook (Expansion in Wavelength)

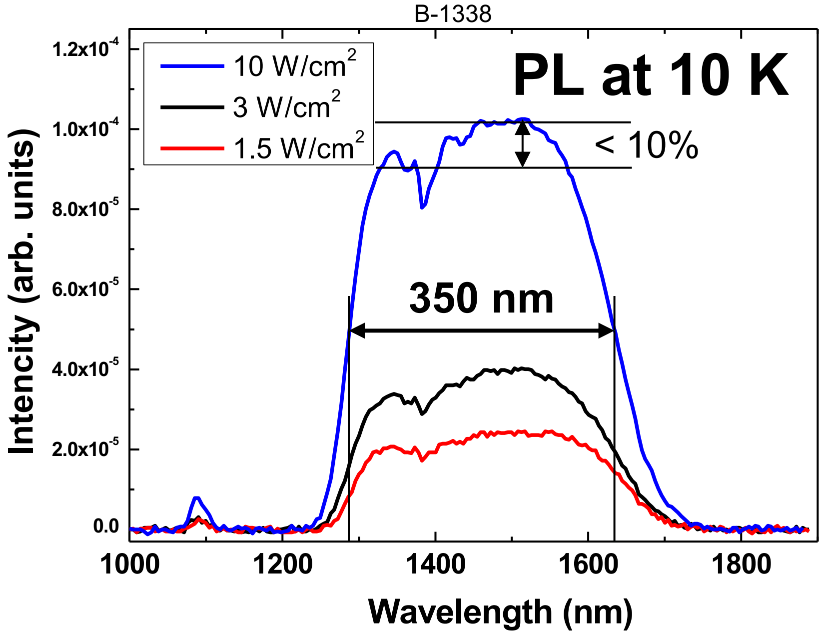
- Beyond 1.55 µm (C+L band)
- 1.3 µm (O-band)

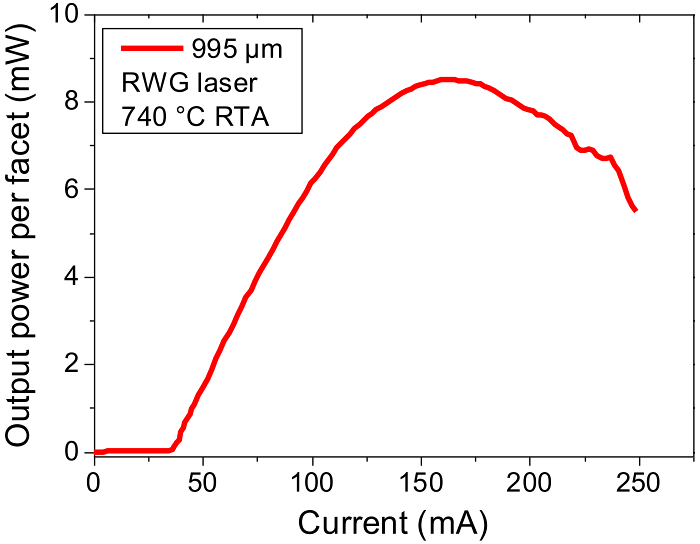
Broadband Light Source (> 300 nm)

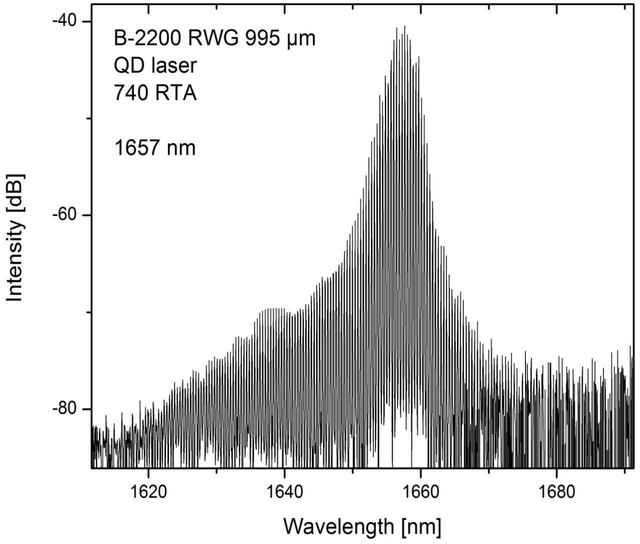
QDs nominal thickness varied in 0.5 ML step



Emission range 1250-1700 nm at 10 K



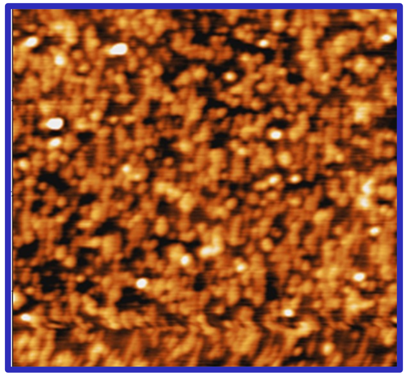




RWG laser emitting at 1.66 µm

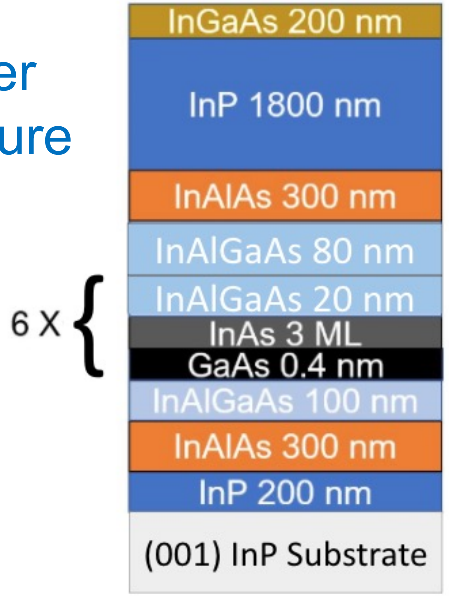
-- unpublished --

1.3 µm InP-Based QD Lasers

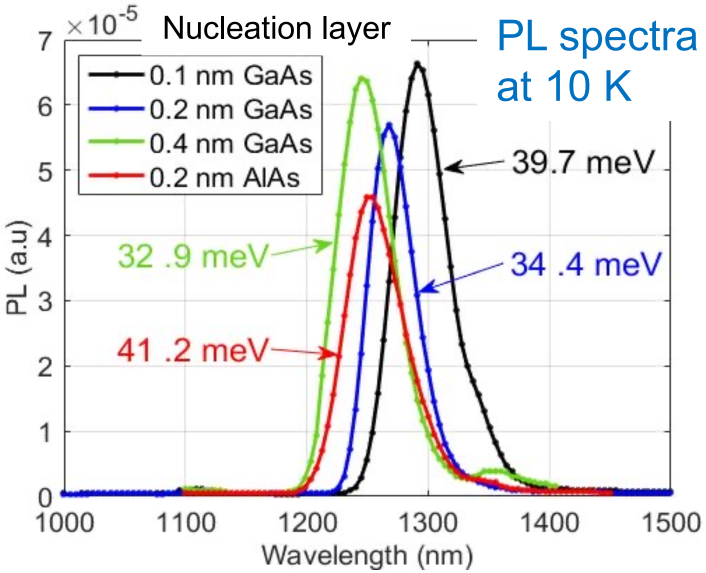


AFM: 2 x 2 µm

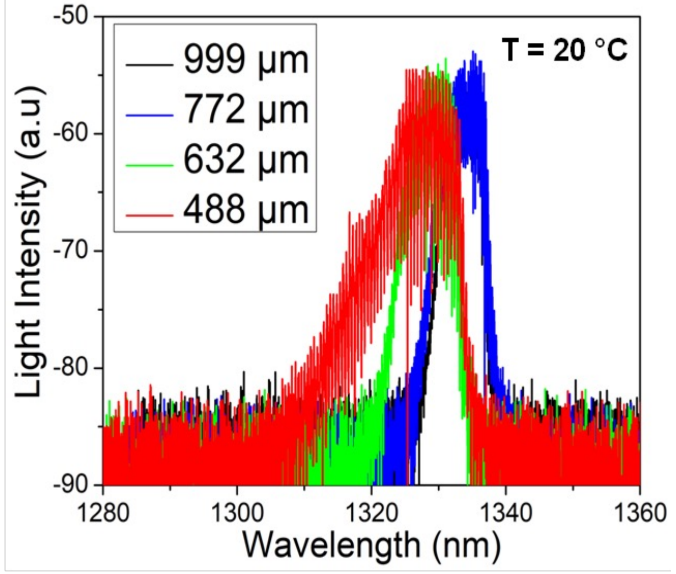
Laser structure

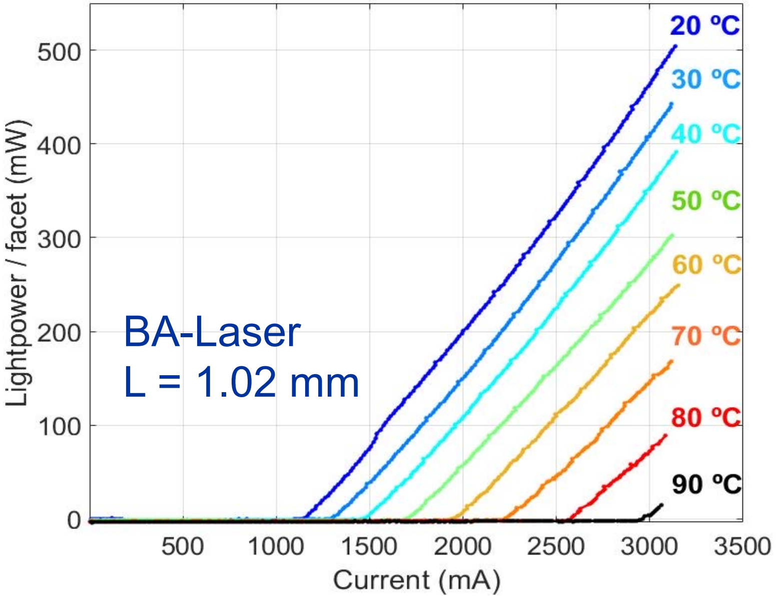


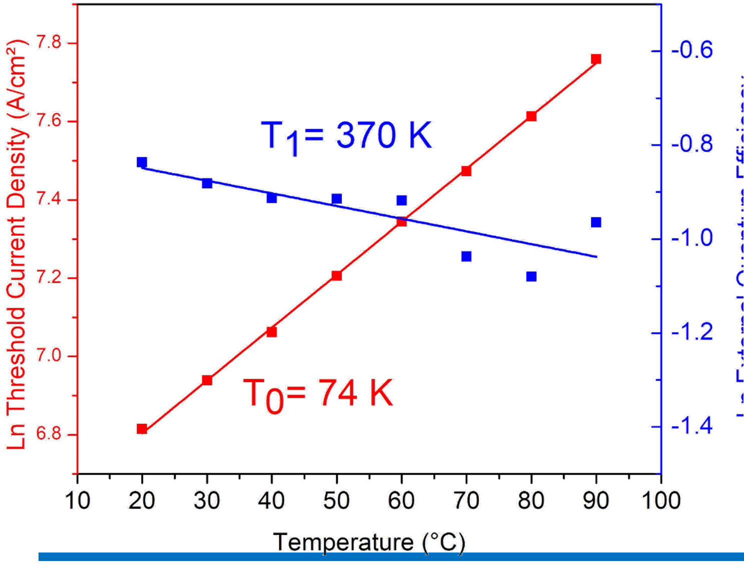
PL spectra at 10 K



Electroluminescence Spectra

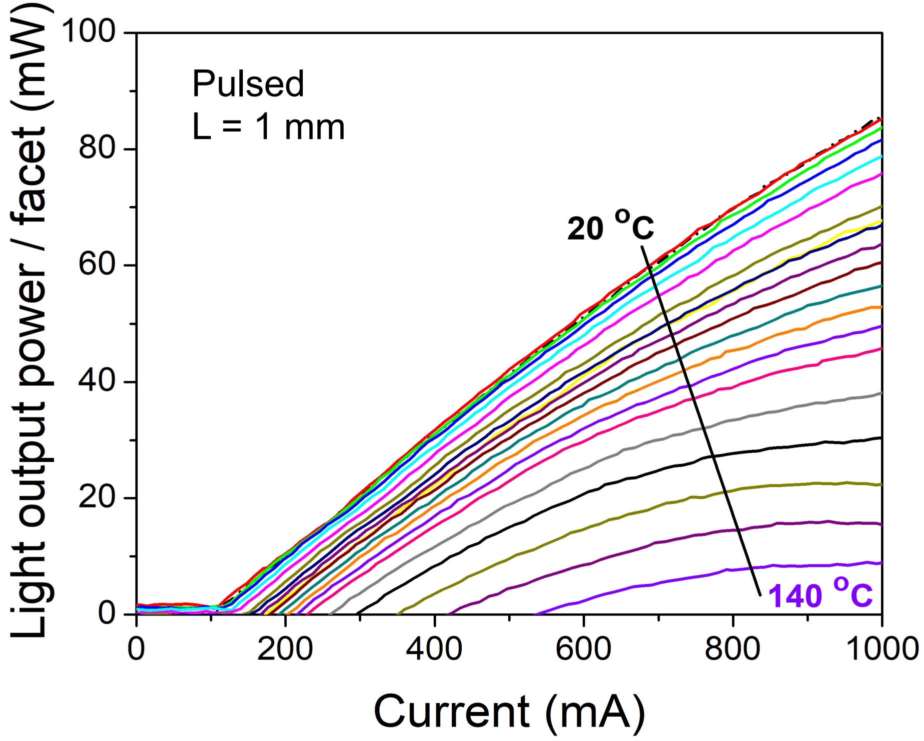




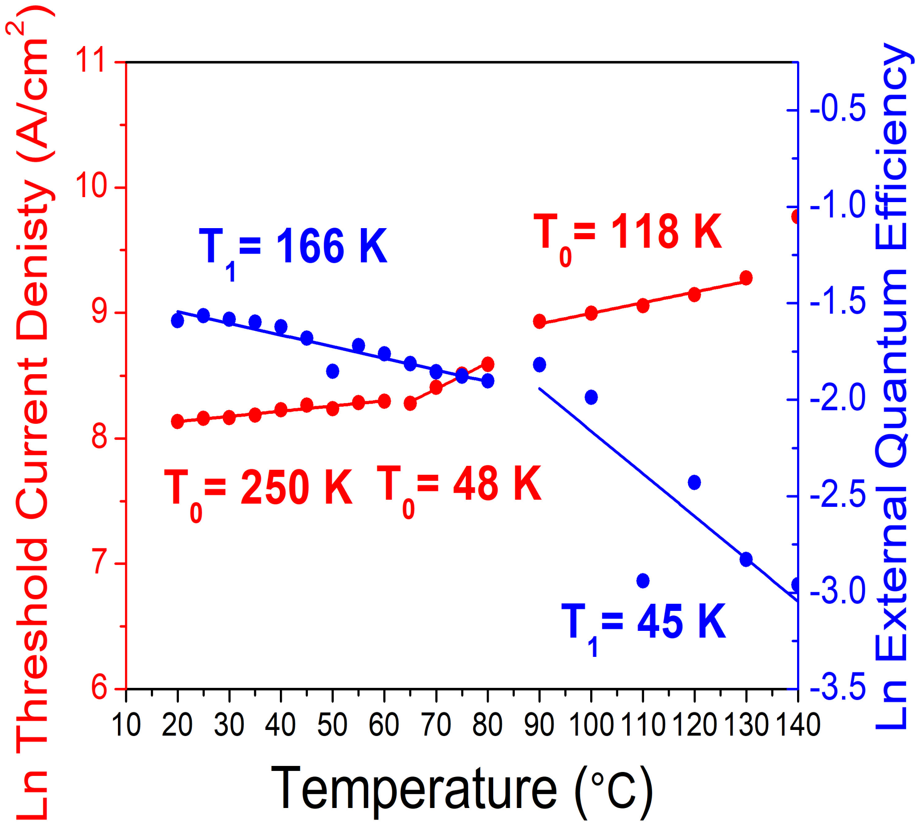


-- sumitted for publication --

Temperature Characteristics of RWG O-band QD laser



- RWG laser with L_c = 1 mm (as-cleaved)



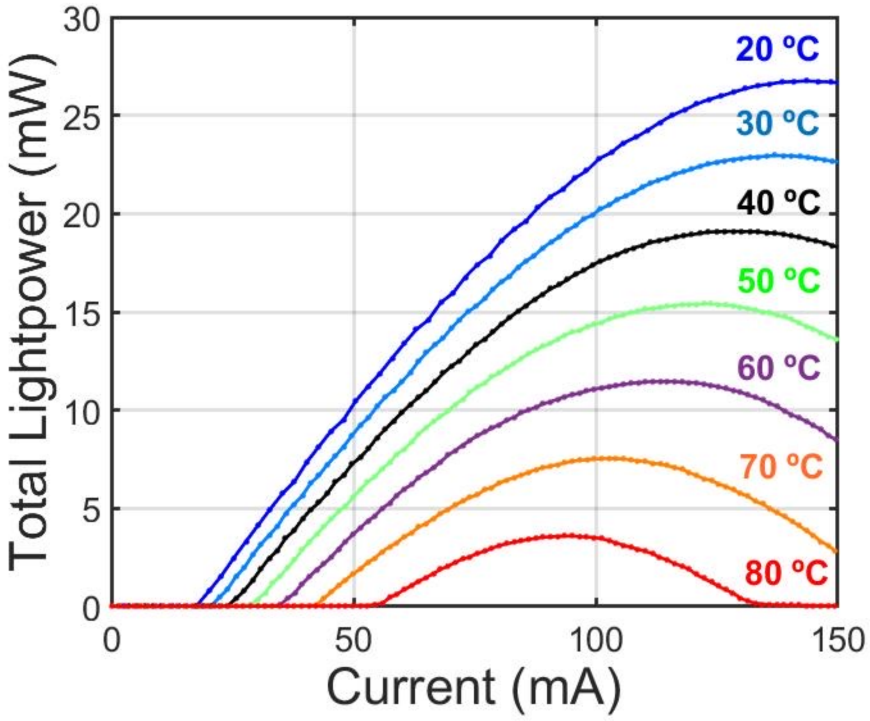
- High T_0 value of 250 K
- T_1 value still very moderate

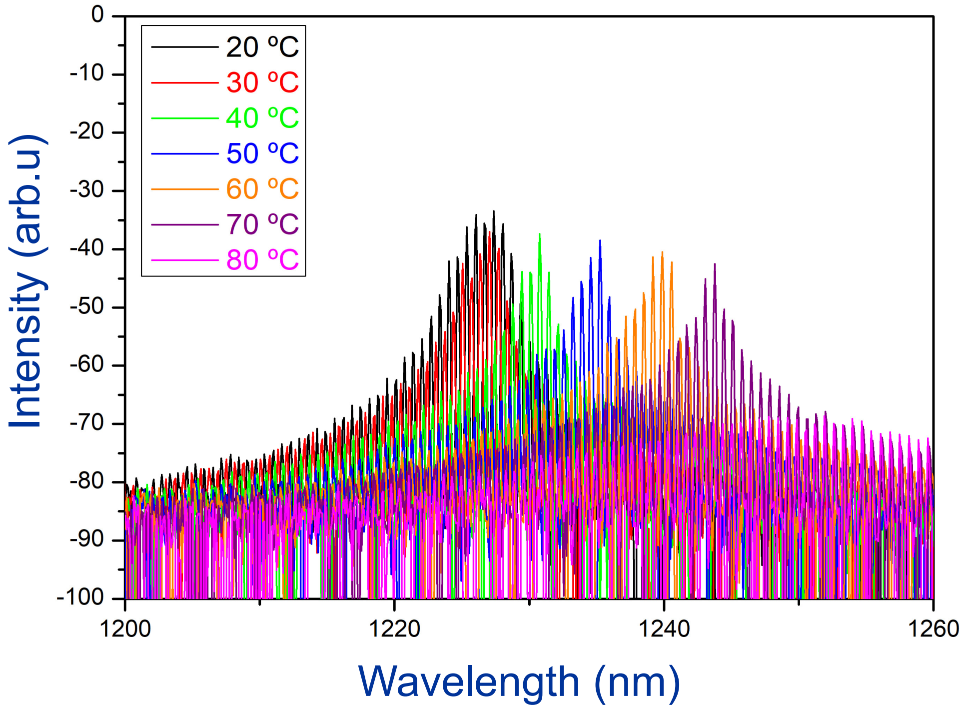
→ further carrier confinement improvement necessary

V. Joshi et al., publication in preparation

CW operation of short cavity RWG laser

Cavity length of 321 µm with back facet HR coated
and front facet as cleaved (ridge width = 2 µm)





- P-I characteristics of short cavity RWG laser
- CW operation up to 80 °C
- 27 mW output power at RT

- Spectra of 321 µm long RWG laser at different operation temperature
- Red shift of wavelength with about 0.3 nm/K

Summary

Quantum Dot Lasers

→ Record values in temperature stability for 1.5 µm lasers
(T_0 = 140 K, T_1 > 900 K)

→ Record values in modulation speed
(26 GBit/s at 80 °C, 25 GBaud PAM4)

Narrow-Linewidth QD-DFB-Lasers

→ Clear proof of impact of QD materials on linewidth narrowing
(one order of magnitude improvement in linewidth by $\alpha < 1$)

→ Ultra-Narrow Linewidth for optimized layer design
(new record linewidth of (20 ± 10) kHz for QD lasers)

Expansion to shorter and longer wavelengths

→ 1.3 and 1.66 µm lasers (O to L band)

→ Broadband gain (> 350 nm bandwidth)

Acknowledgements

EU Projects:

DELIGHT GOSPEL SEQUOIA MITEPHO moicana

BMBF Project:

Federal Ministry of Education and Research

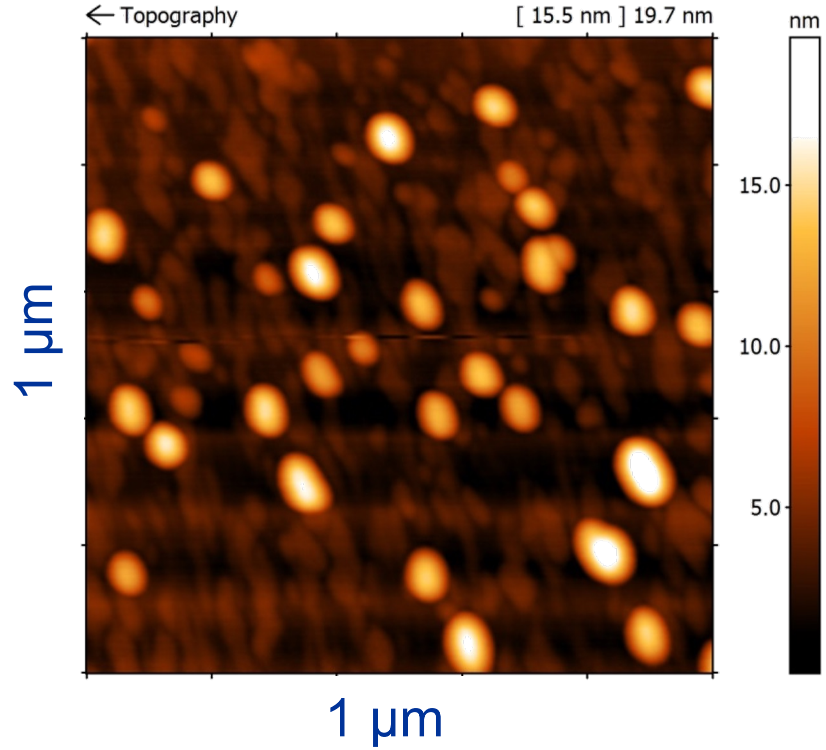
PEARLS

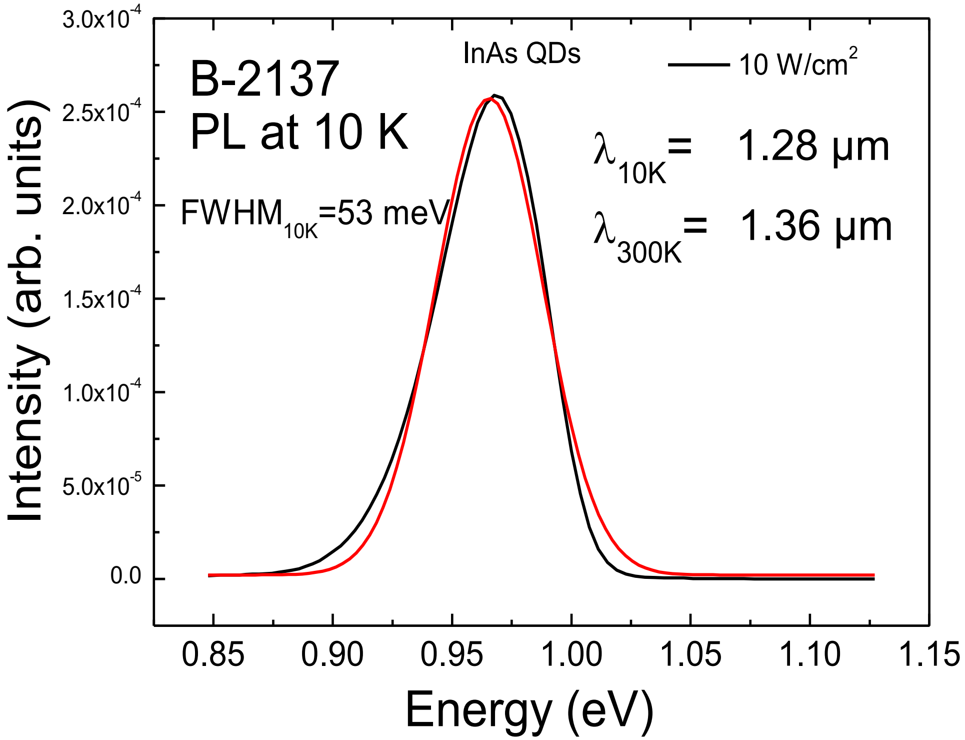
Israeli Funding:
- Israel Science Foundation
- Israeli Innovation Authority (project Peta Cloud)

Thank you for your kind attention

First growth of smaller QDs

3.0 ML InAs QDs; T_S = 480 °C; V/III ratio = 27

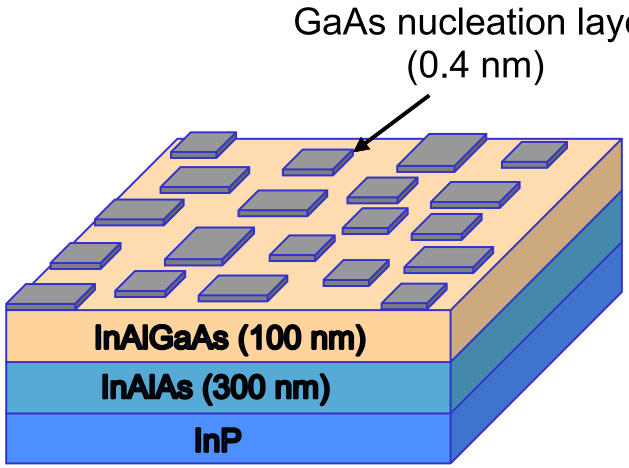


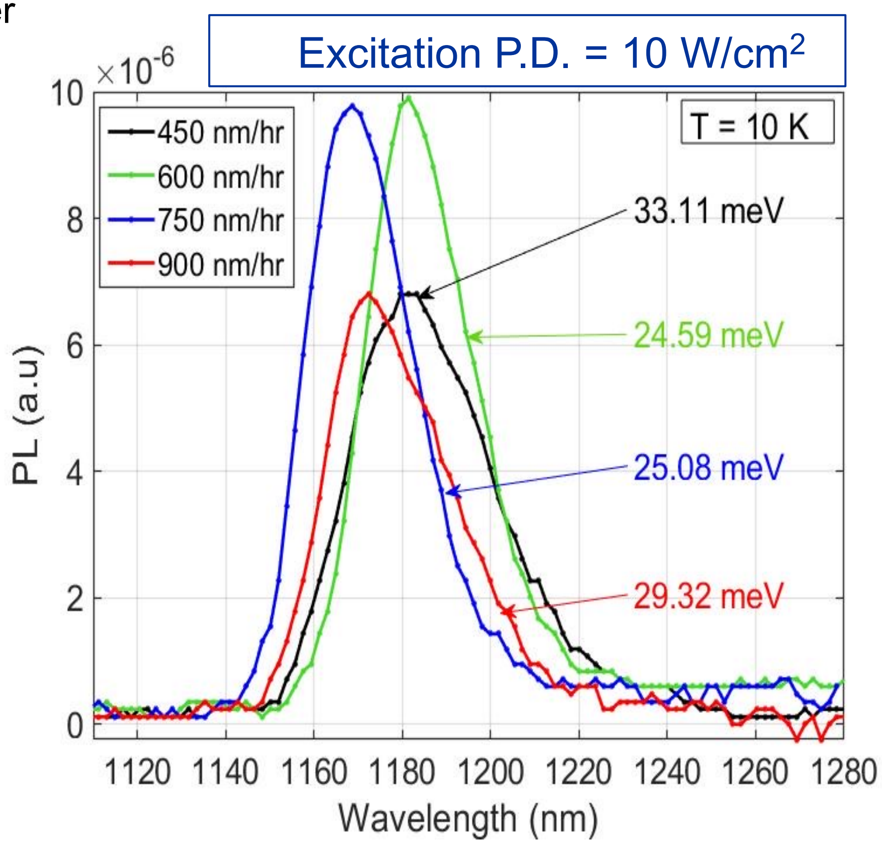


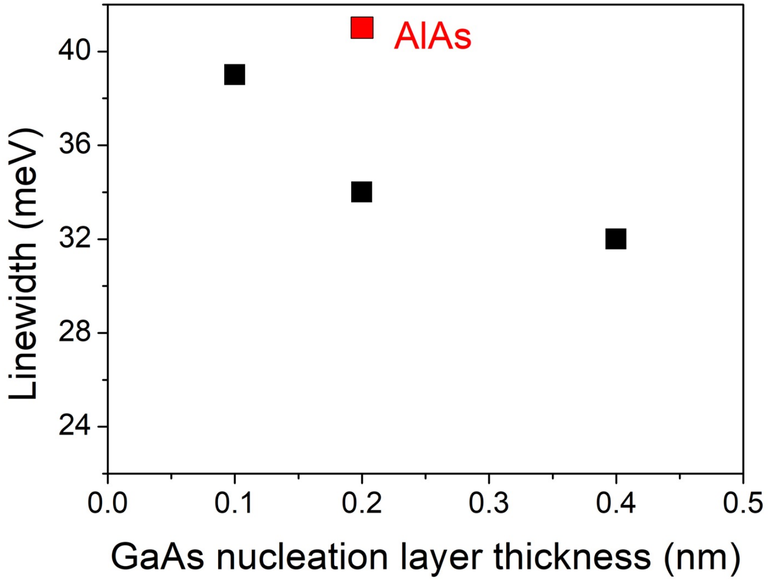
High-density QD growth at 1.3 µm not possible by only adapting standard growth parameters

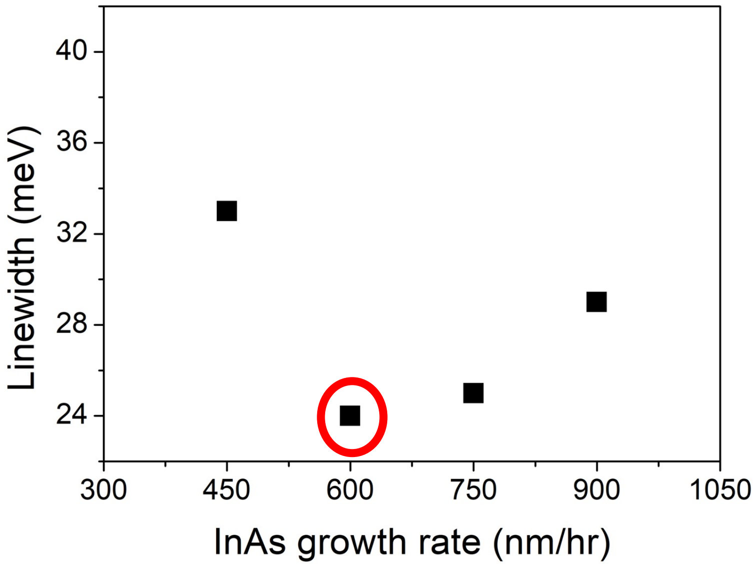
- Nominal thickness of QD layer
- V/III ratio
- Growth temperature

Introduction of additional strained nucleation layer

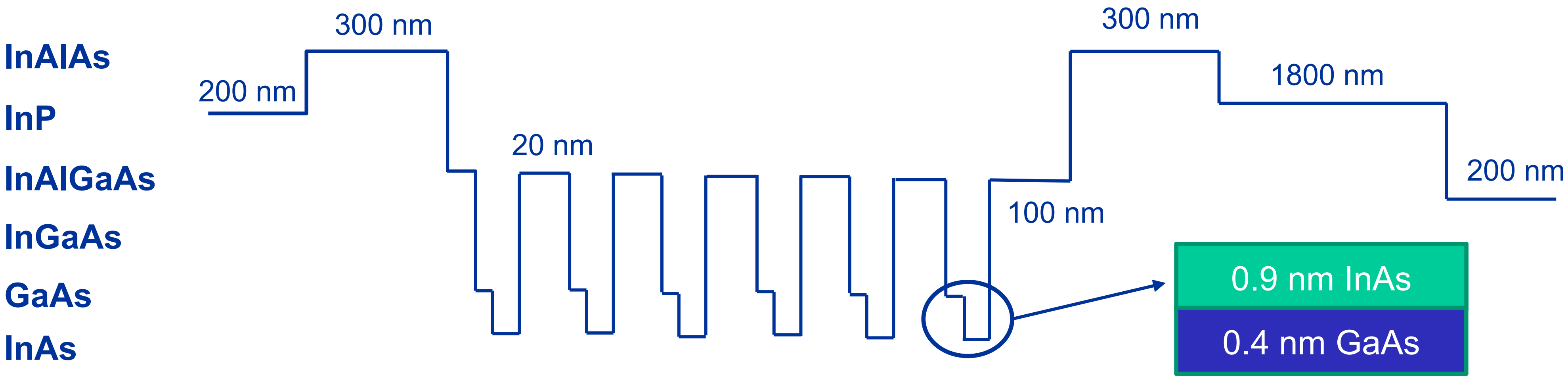


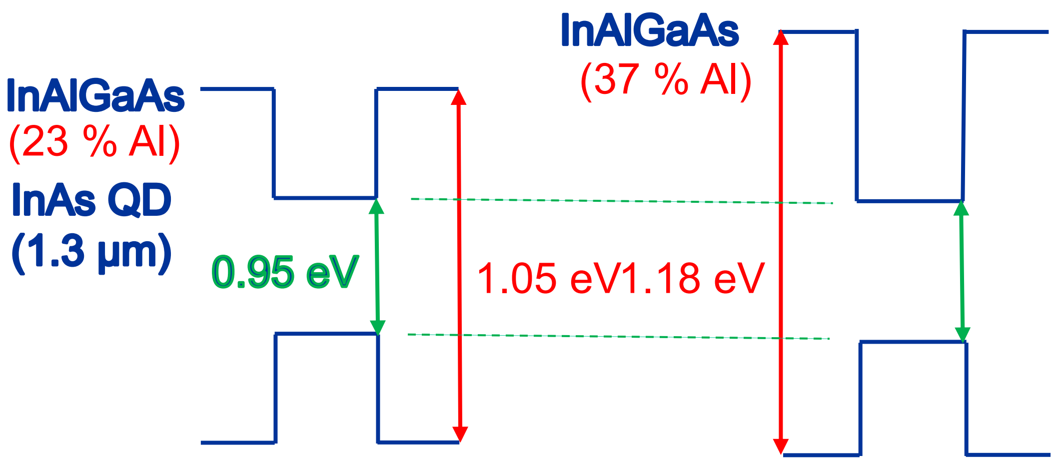






- Variation of nucleation layer thickness and growth rate
- Reduction from 53 meV (low QD density) to 24 meV (high QD density)
- < 1.3 µm emission possible with increasing nucleation sites





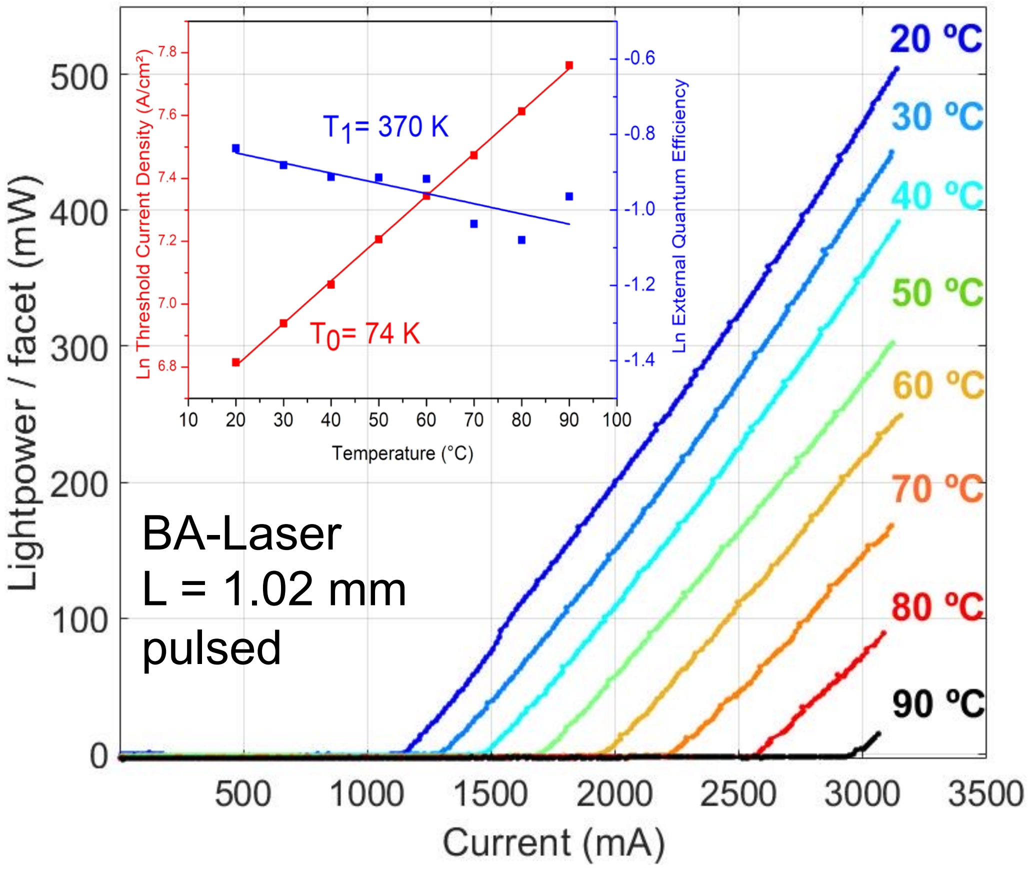
Initial laser design

Improved laser design

- Initial design used same barriers than 1.55 µm QD lasers.
  (➔ limited carrier confinement)
- Improved design with increased barrier height to obtain similar confinement for 1.3 µm QDs than for 1.55 µm QDs.

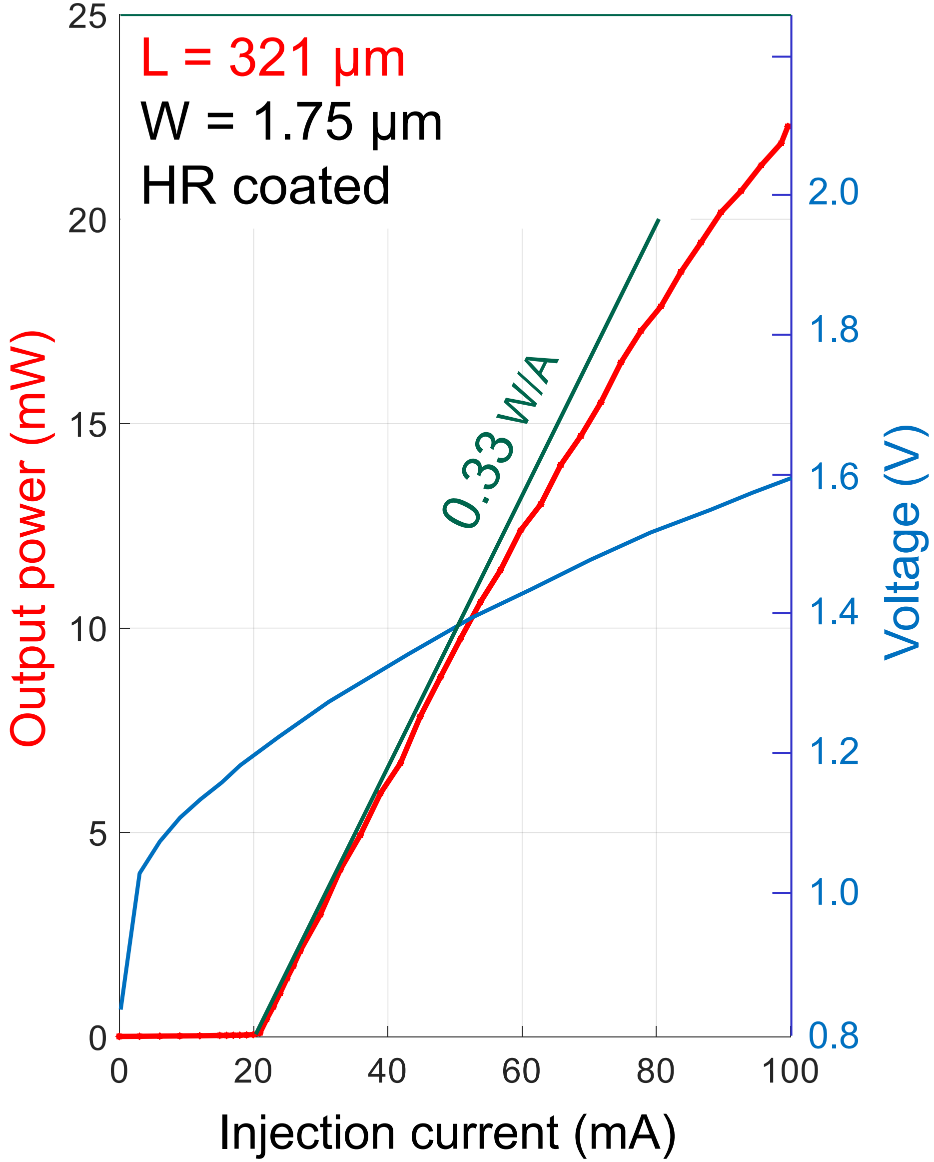
BA Laser evaluation

Parameter	Initial	Improved
λ (µm)	1.36	1.22
J_{th} (kA/cm^2)	0.72	0.67
η_i	0.68	0.82
α_i (cm^{-1})	8.8	11.3
J_0 (kA/cm^2)	0.46	0.47
Γ g_0 (cm^{-1})	78	91
Γ g_0 (cm^{-1}) per QD layer	**13**	**15**

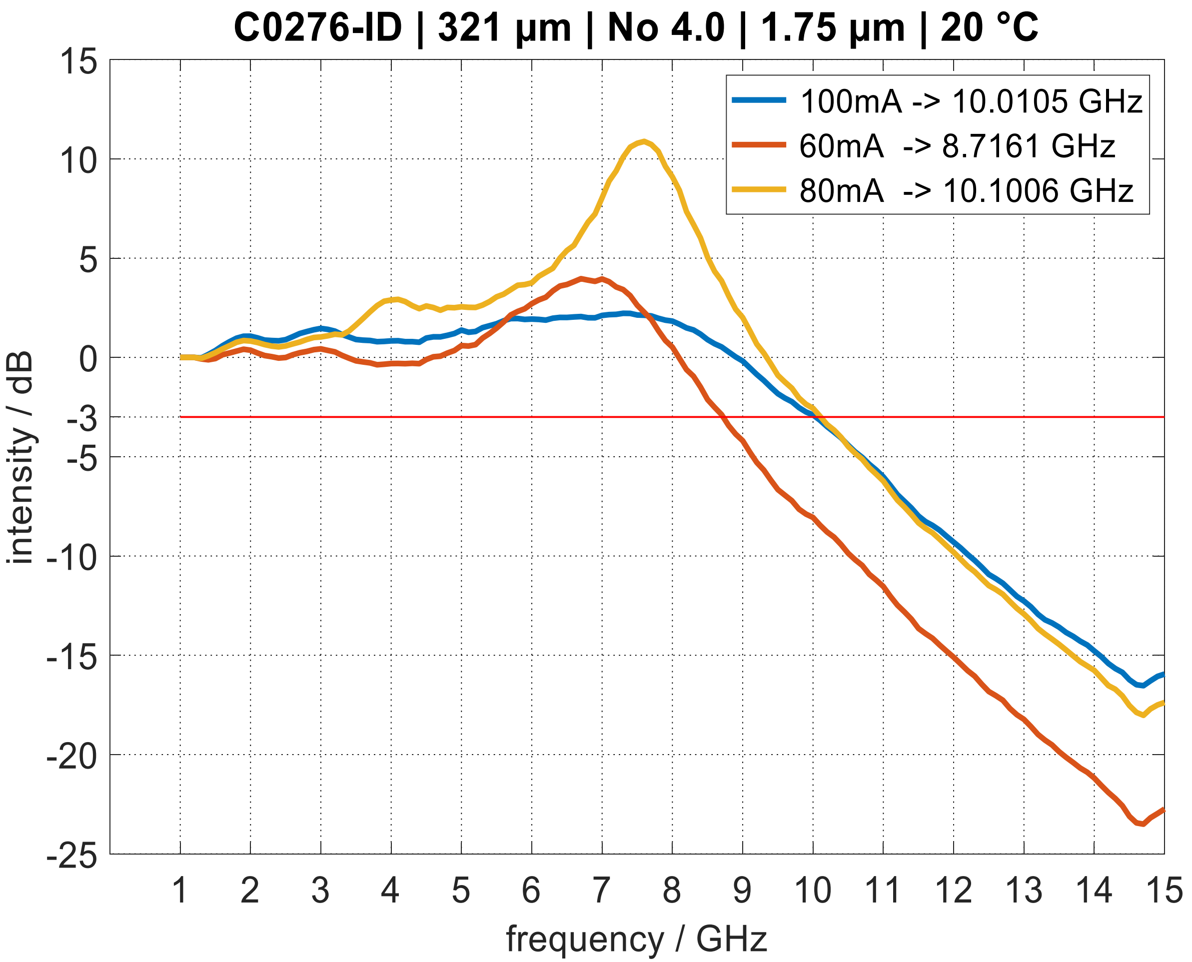


- 100 µm broad area laser (cleaved facets, variable cavity lengths)
- Improved internal quantum efficiency due to better carrier confinement
- High modal gain up to 15 cm^{-1} per QD layer similar to 1.55 µm QD lasers

SSM response of short cavity RWG laser



Small Signal Modulation



- SSM bandwidth of 10 GHz (at 20 °C)