Thermal management of Packaged QCL

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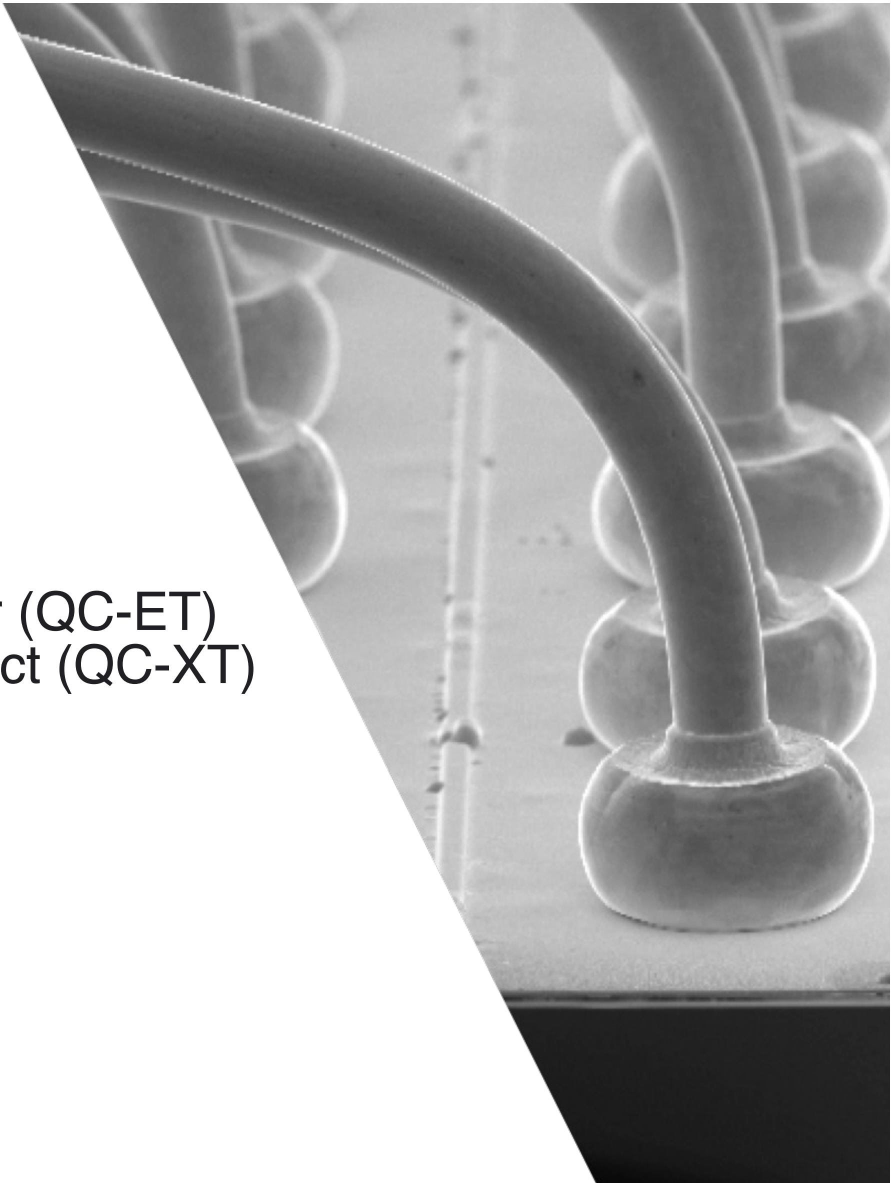
Swissphotonics Workshop: Thermal Management in Photonics Packaging, Neuchâtel, April 3rd 2019

Outline

- Company presentation
- Dissipation simulations
- Extended tuning with integrated heater (QC-ET)
- Extended tuning based on Vernier effect (QC-XT)



ALPES LASERS

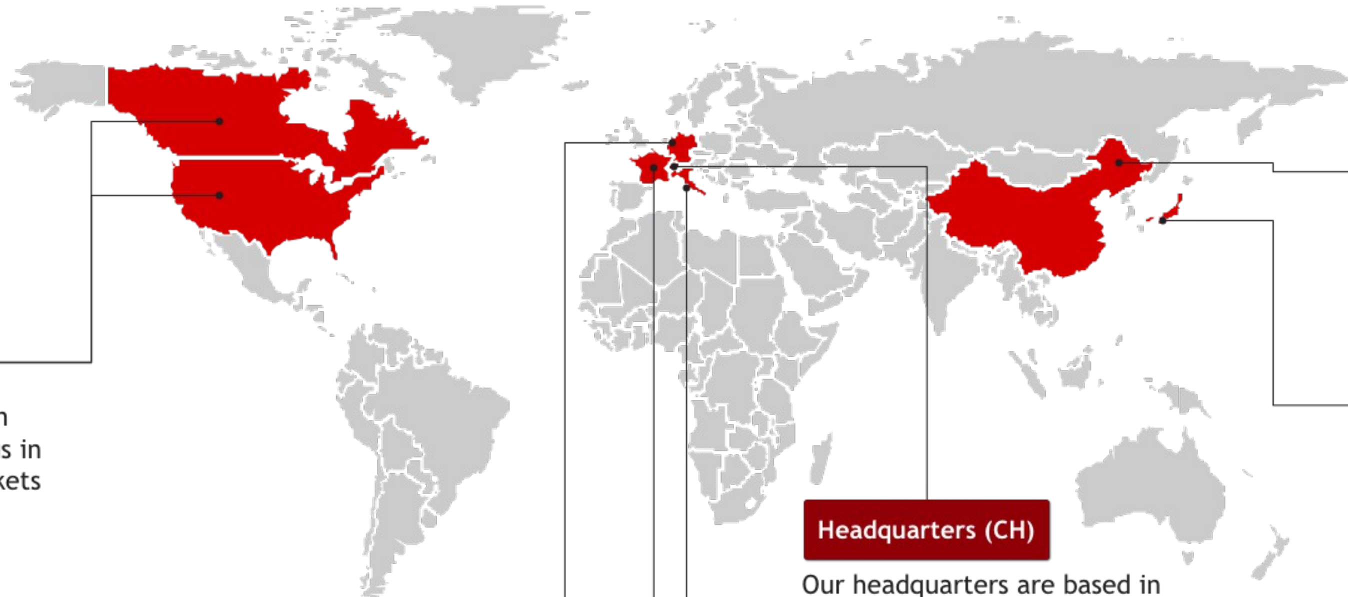
ALPES LASERS
Quantum Cascade Technologies

Design & production of infrared photonics

- First company to produce QCLs (founded 1998)
- Located near Neuchâtel (Switzerland)
- Innovation driven
- High-level team of experts
- Strong proprietary know-how
- IPR - 12 major patents in QCLs

20 years of global presence

With distributors in DE, FR, IT, US, CA, JP, CN



US & Canada

Local distributors Boston Electronics represents us in the US and Canada markets

China

Local distributors Universal Hong Kong Technology Co Ldt represents us in the Chinese market

Japan

Local distributors Keystone International Co. Ltd represents us in the Japanese market

Headquarters (CH)

Our headquarters are based in St-Blaise in Switzerland, in the Canton of Neuchâtel

Germany

Local distributors MG Optical Solutions represents us in the German market

France

Local distributors Opton Laser International represents us in the French market

Italy

Local distributors Energy Laser Srl represents us in the Italian market

Alpes product offering

A wide range of photonic solutions

Laser sources 01

Quantum Cascade Lasers
- Pulsed DFB QCL
- Continuous-Wave DFB QCL
- Pulsed FP/Broad Gain QCL
- High Power Pulsed FP QCL
- Custom developments

Interband Cascade Lasers
Diodes Lasers
Pulsed FP THz QCL (cryogenic)

Electronics 02

Electronic Drivers (Pulsed/CW)
- S-2 Driver
- S-3 Driver
- S-4 Driver

Temperature Controller TC-3

Subcomponents 03

External Cavity Laser kit
Pigtailed components/lasers
Laser/photodetector assemblies
Custom systems

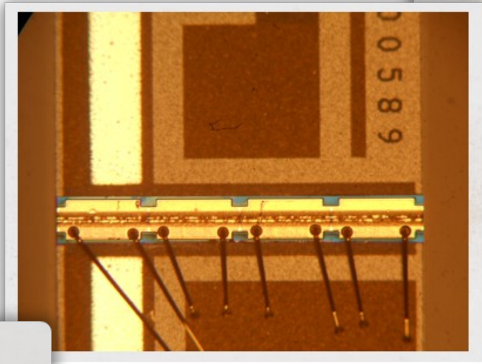
Laser housing options

Select the one suitable for your needs

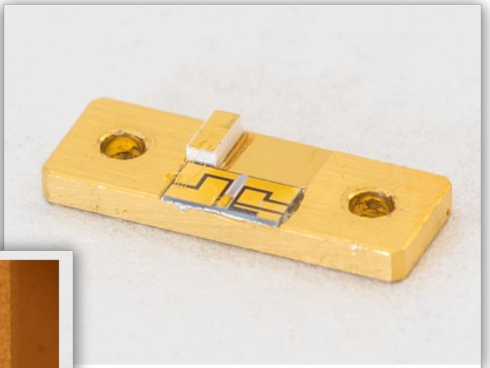
LLH

TO3

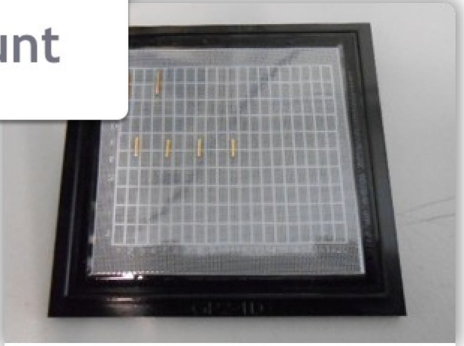
HHL



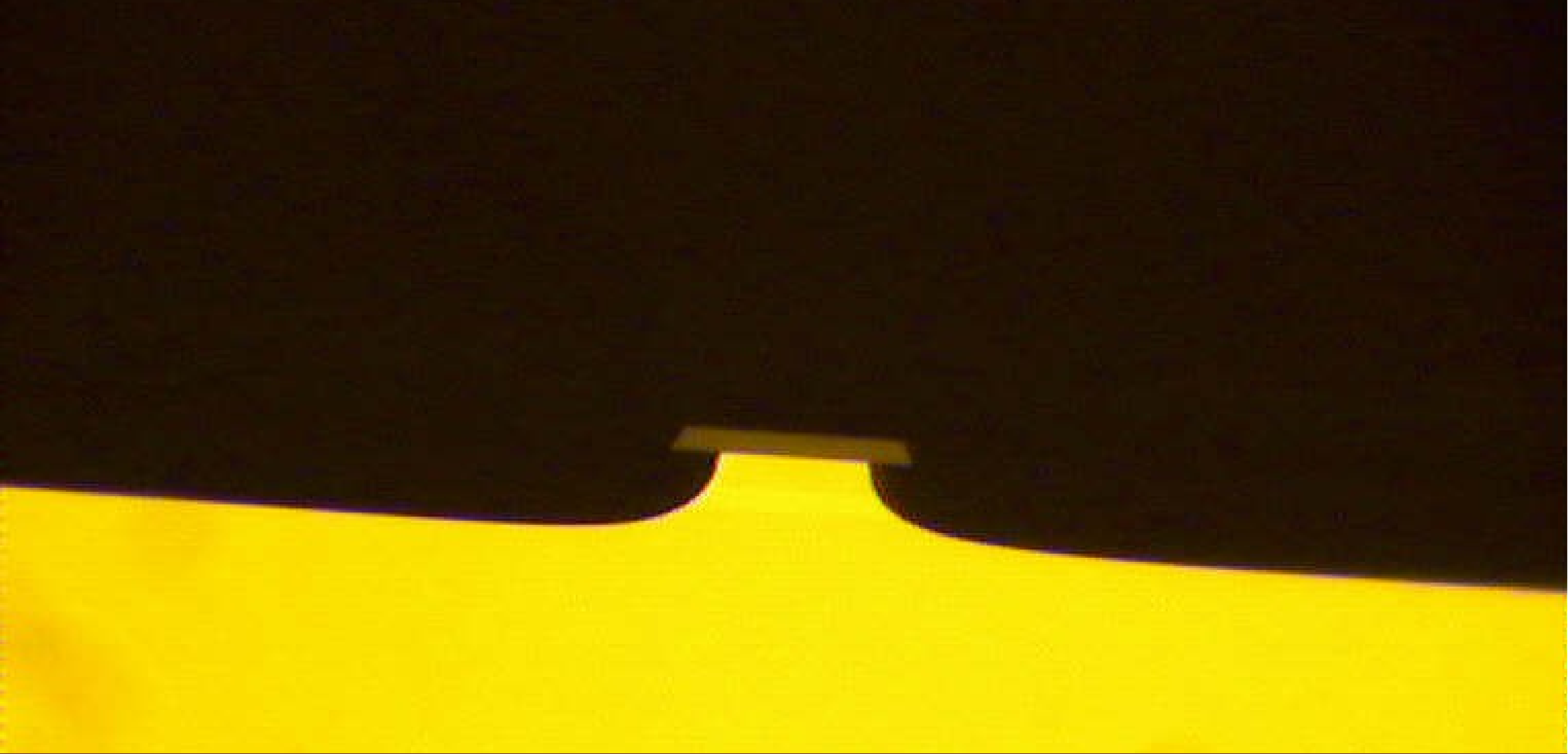
AlN submount



Cu submount



Bare chip



Introduction

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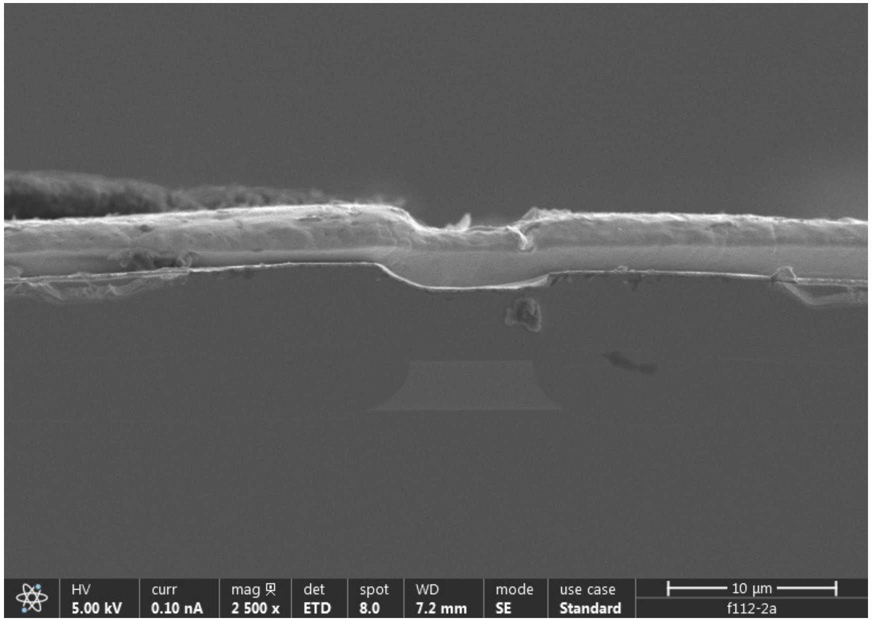
Heat transfer in QCLs

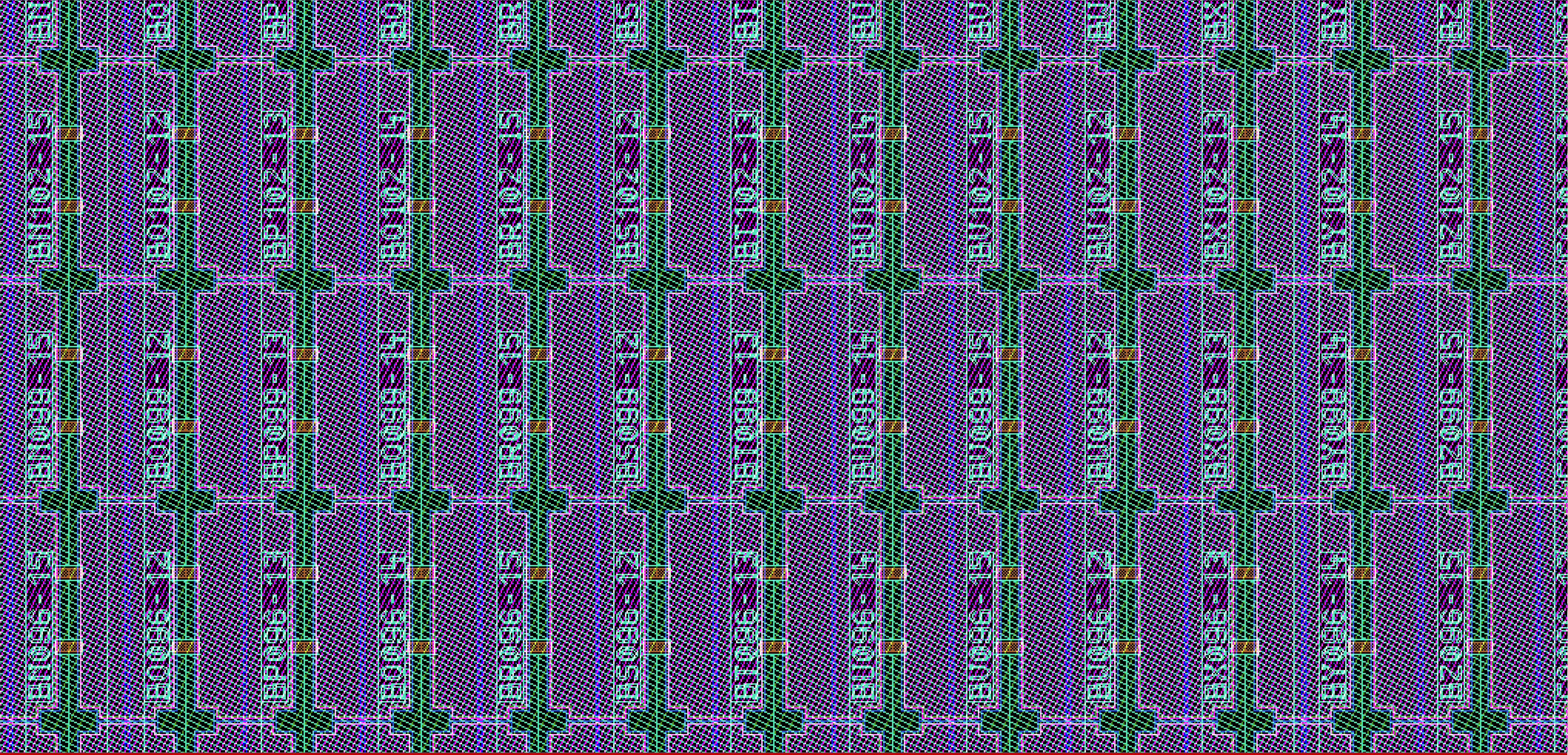
QCL heat dissipation (continuous-wave operation):

- Max voltage: V_{max} = 12-15 V
- Max. current density: J_{max} = 3-5 kA/cm^2
- Heat dissipation per unit volume: P_{el} = 2-5 x 10^8 kW/cm^3

Active region thermal conductivity:

- Parallel to layers: $k_{//}$ = 9.0 W/(mK)
- Perpendicular to layers: $k_{\perp}$ = 2.2 W/(mK)





Simulations of various configurations

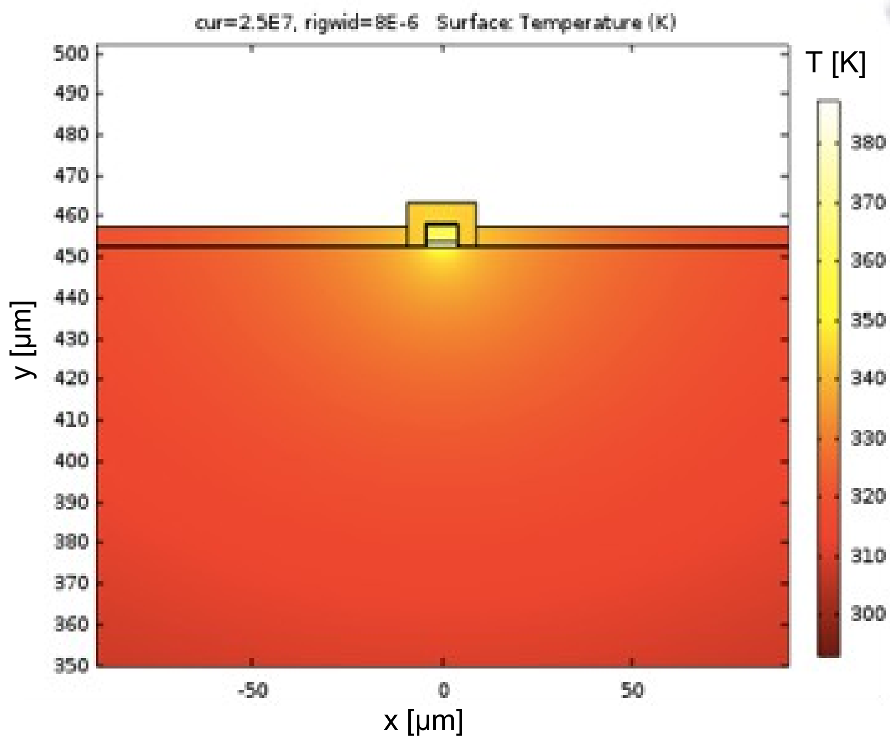
Material parameters (room temperature)

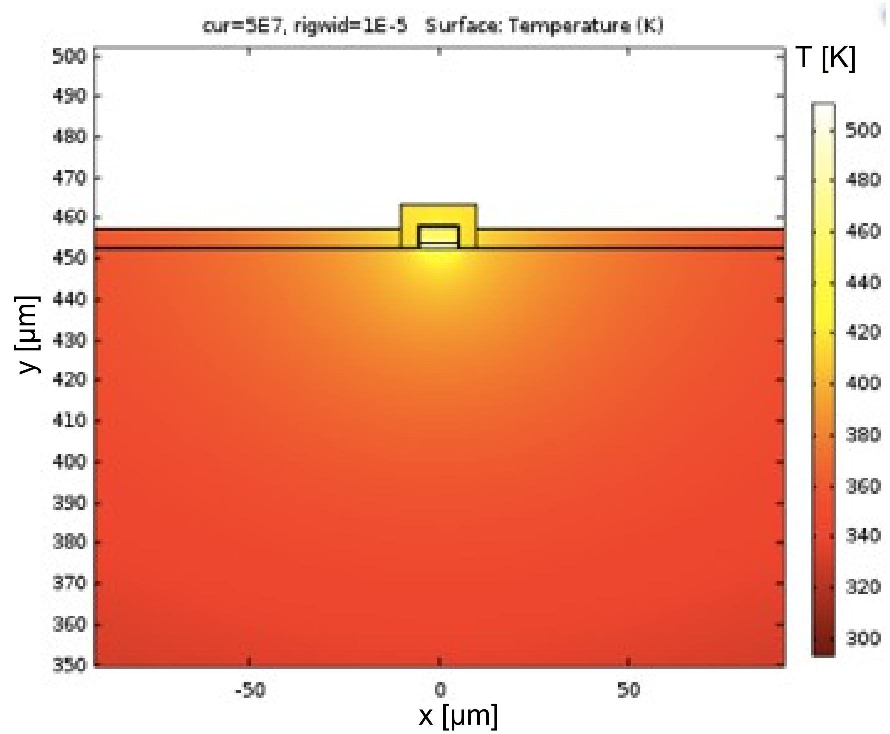
layer	material	thicknes [um]	Doping [cm-3]	n_r	n_i	El cond [S/m]	thermal cond [W/(m.K)]	density [kg/m-3]	specific heat capacity [J/(kg.K)]
heatsink holder	copper	-	-				385	8900	387
solder	indium	-	-				86	7310	233
submount	AlN	300	-				170	3260	740
solder	AuSn	2.5	-			6e6	57	14700	150
el. plated contact	gold	4	-	12.0742	60.35309	4e7	318	19300	129
top contact	InGaAs	0.2	1e19	0.1777	3.058111		4.6	5500	300
high dop clad	InP	1	8e18	0.322	0.808011	6.9e5	59	4810	310
mid dop clad	InP	4	5e16	3.0315	0.000536		59	4810	310
low dop clad	InP	3	2e16	3.0376	0.000214	2592	59	4810	310
active region (x)	InGaAs/ AlInAs	3.5	-	3.2655	0		9.0	5000	300
active region (y)	InGaAs/ AlInAs	3.5	-	3.2655	0		2.2	5000	300
substrate	InP	150	1e16	3.0396	0.0001		59	4810	310
regrowth	InP	-	0	3.0416	0	1e-15	59	4810	310
isolation layer	SiO	0.3	-				1.25	3180	160
isolation layer	Si3N4	0.3					25.5		

Heat transfer in various configurations

Basic configuration:

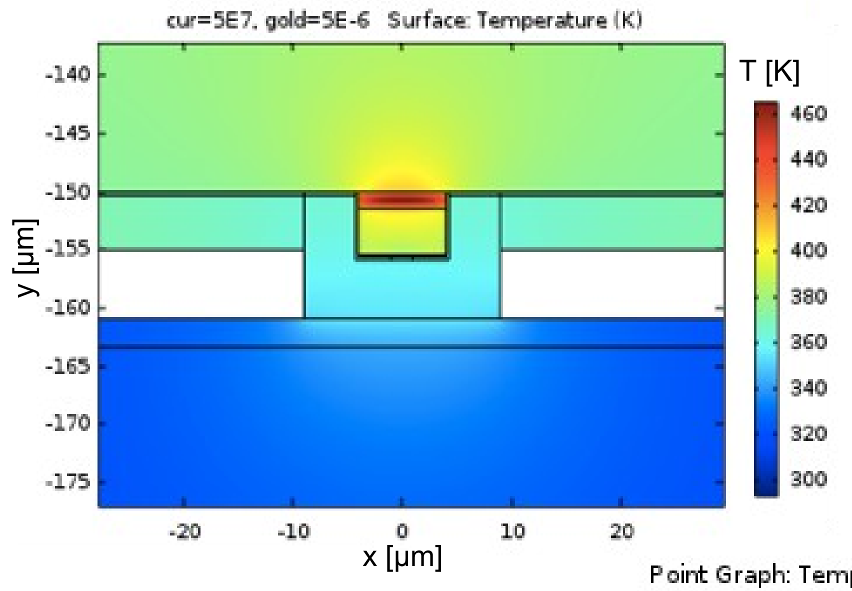
- Ridge waveguide (RWG) processing
- Epitaxial-side-up (epi-up) bonding

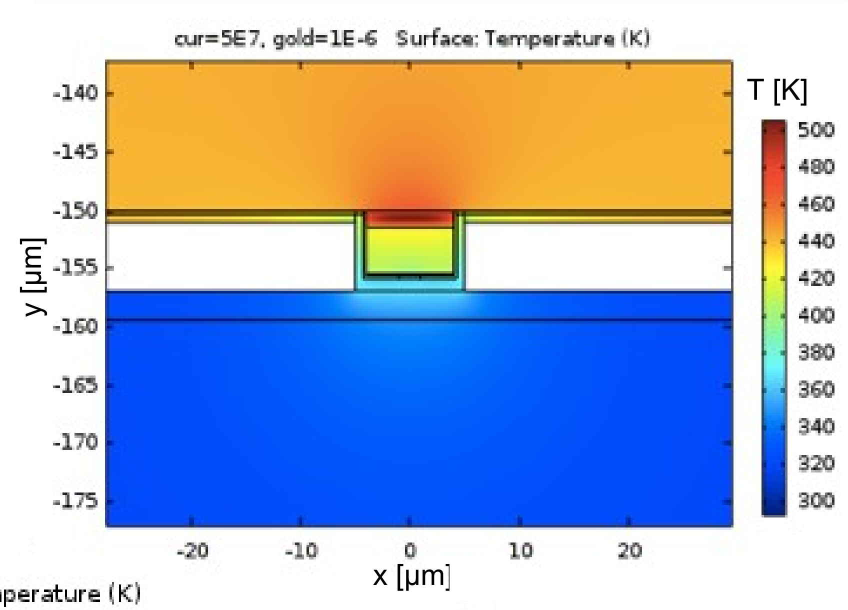




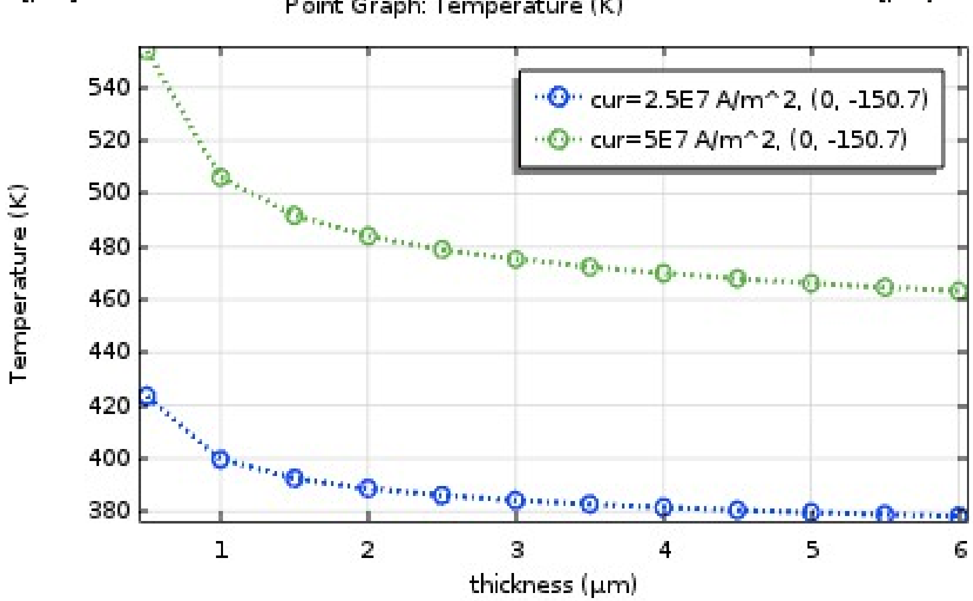
Current density	w=8um	w=10um
J=2.5 kA/cm^2	390 K	404 K
J=5 kA/cm^2	485 K	513 K

Impact of electroplated gold thickness





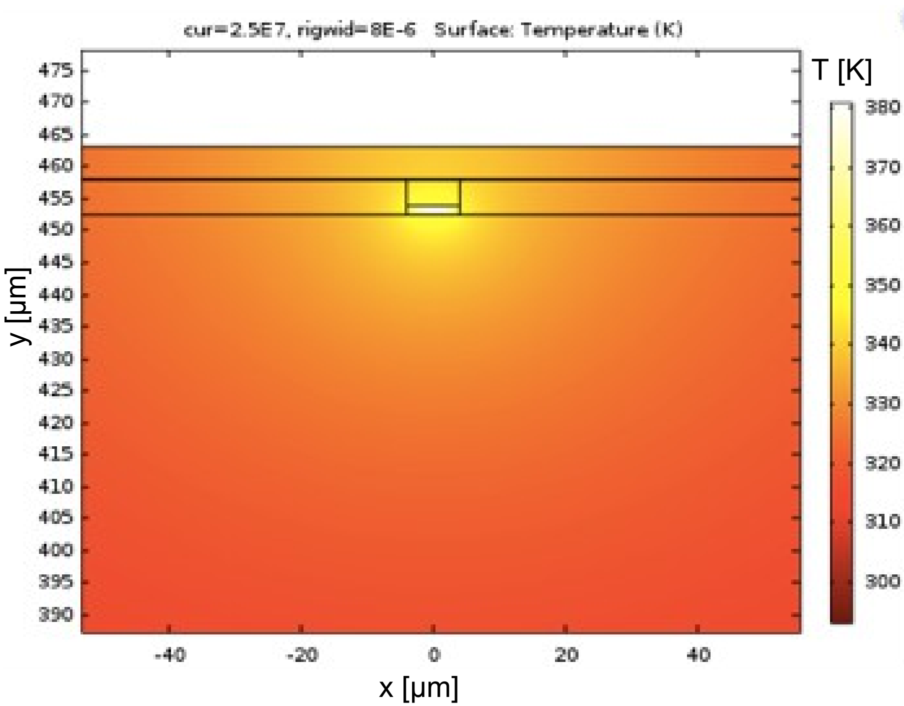
- RWG processing
- w = 10 μm
- Epi-down bonding

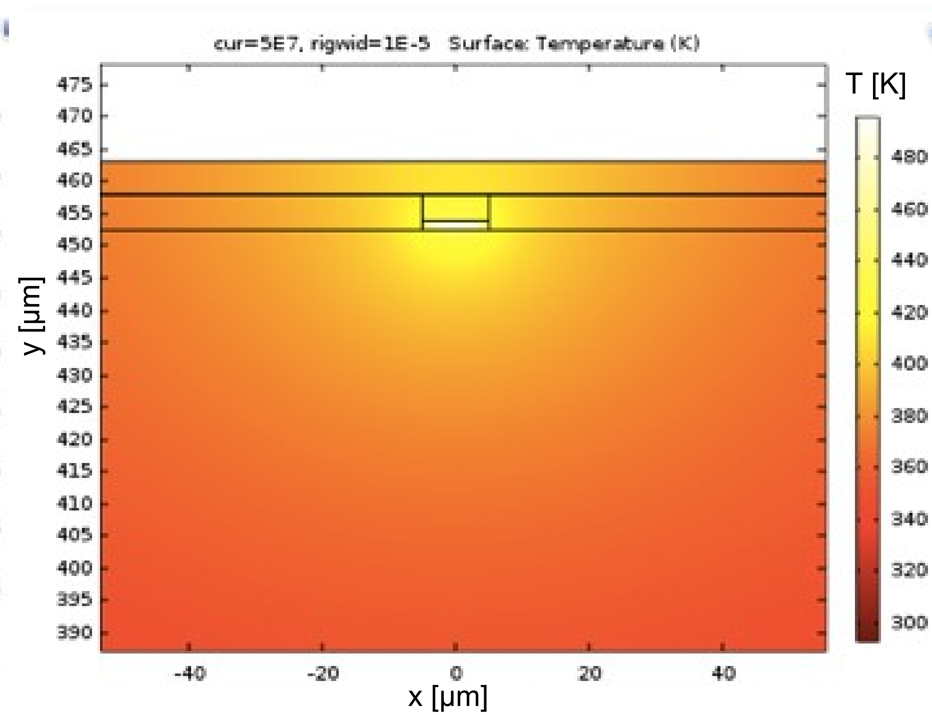


Heat transfer in various configurations

Intermediate configuration:

- Buried heterostructure (BH) processing
- Epi-up bonding



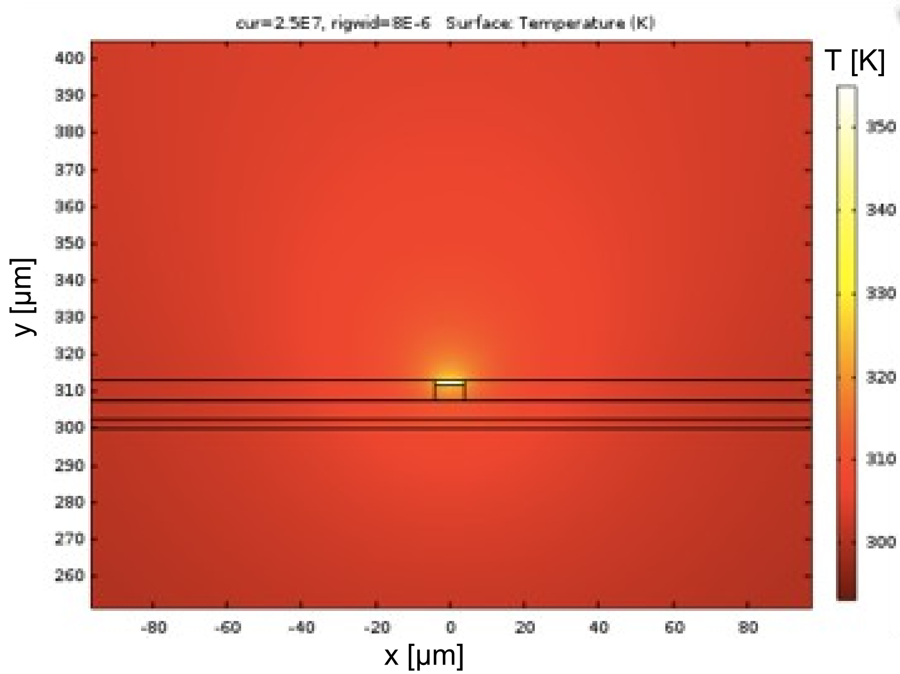


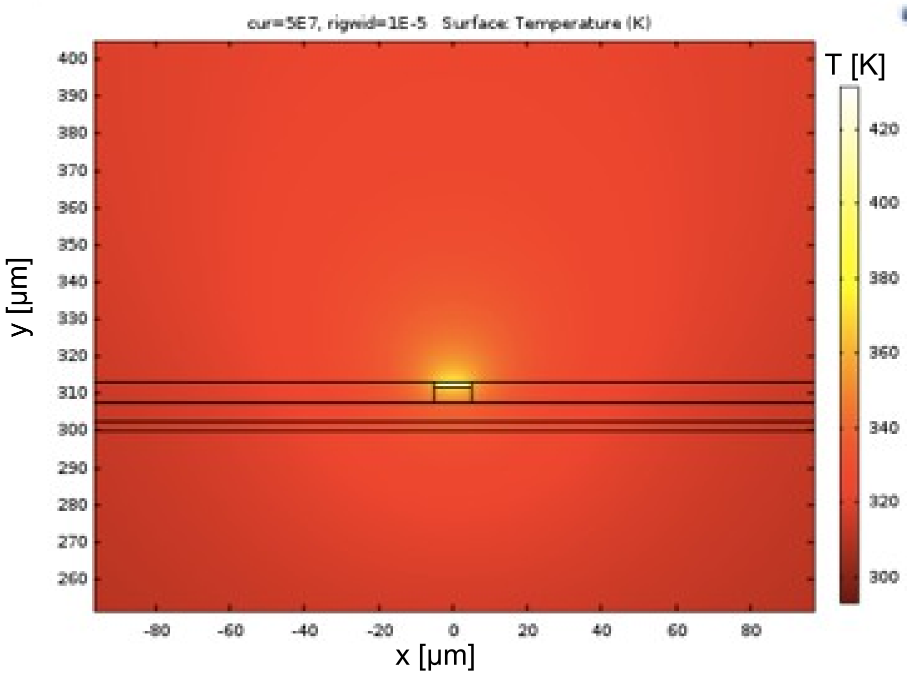
Current density	w=8um	w=10um
J=2.5 kA/cm^2	380 K	395 K
J=5 kA/cm^2	470 K	496 K

Heat transfer in various configurations

Optimized configuration:

- BH processing
- Epi-down bonding

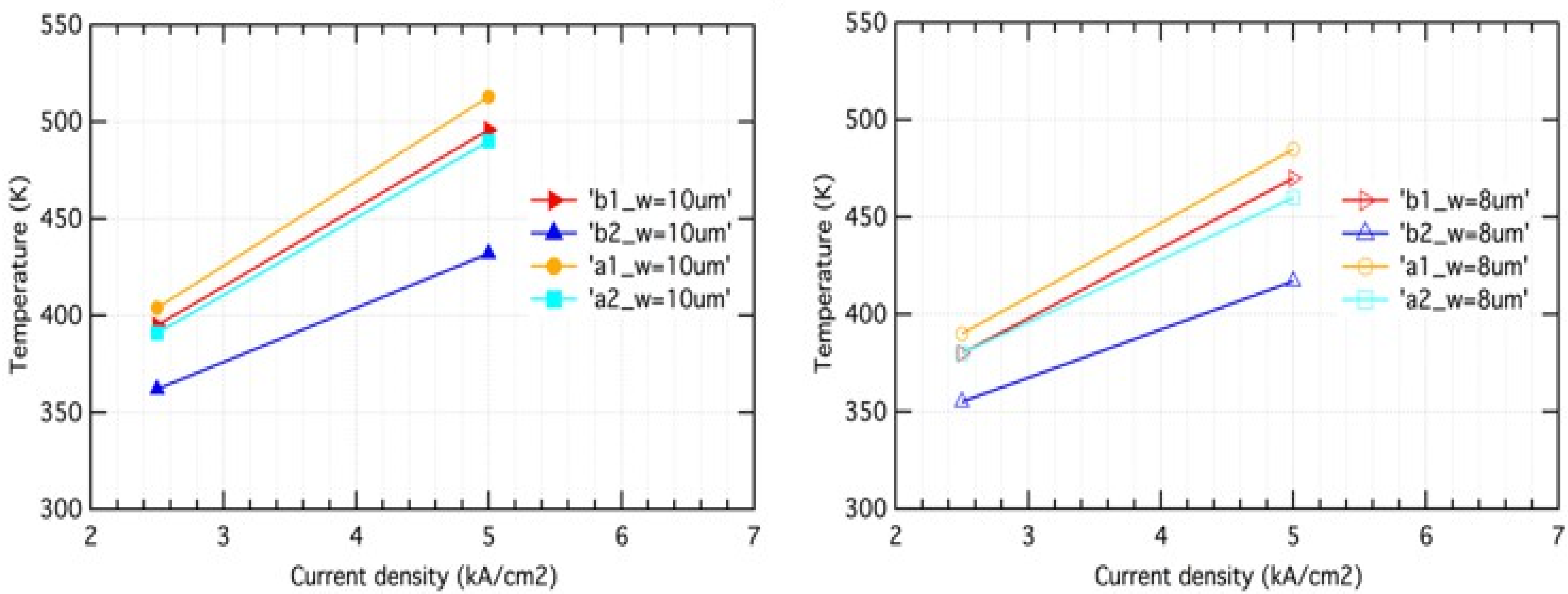




Current density	w=8um	w=10um
J=2.5 kA/cm^2	354 K	363 K
J=5 kA/cm^2	415 K	430 K

Comparison of various configuration

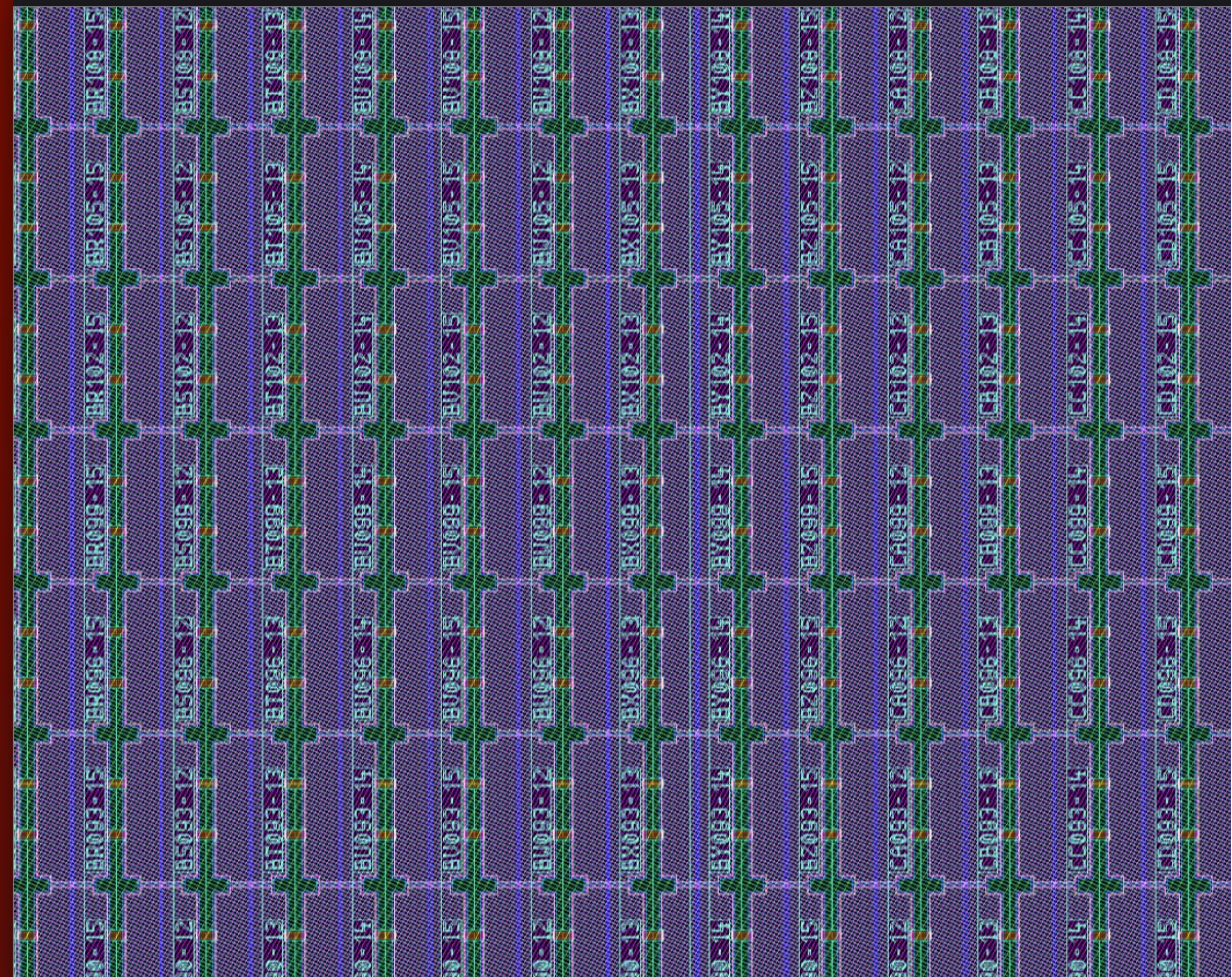
a1: RWG, epi-up	b1: BH, epi-up
a2: RWG, epi-down	b2: BH, epi-down



- Worse heat dissipation: RWG, epi-up
- BH epi-up and RWG epi-down have similar performance
- Significant improvement in BH epi-down configuration

High power QCLs

HP-QCL



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High power QCLs

Core technical device characteristics

- High power QCL activity started 5 years ago
- Watt-level multimode devices at λ = 4.0, 4.6, 4.9, 9.0, and 9.7 *μ*m
- Demonstrated 1 W narrow-band (< 1 cm^{-1}) devices at 4.7 *μ*m
- Developed ruggedized packaging for defense application
  - Excellent beam pointing precision and stability
  - Sustain shocks, vibrations, extreme ambient and storage temperatures
- Fully packaged collimated QCLs currently available:
  - 1.5 W at λ = 4.55, 4.65, and 4.90 *μ*m
  - 1.0 W at λ = 3.95 *μ*m
  - 1.0 W at λ = 9.05, 9.70 *μ*m
- OEM driver

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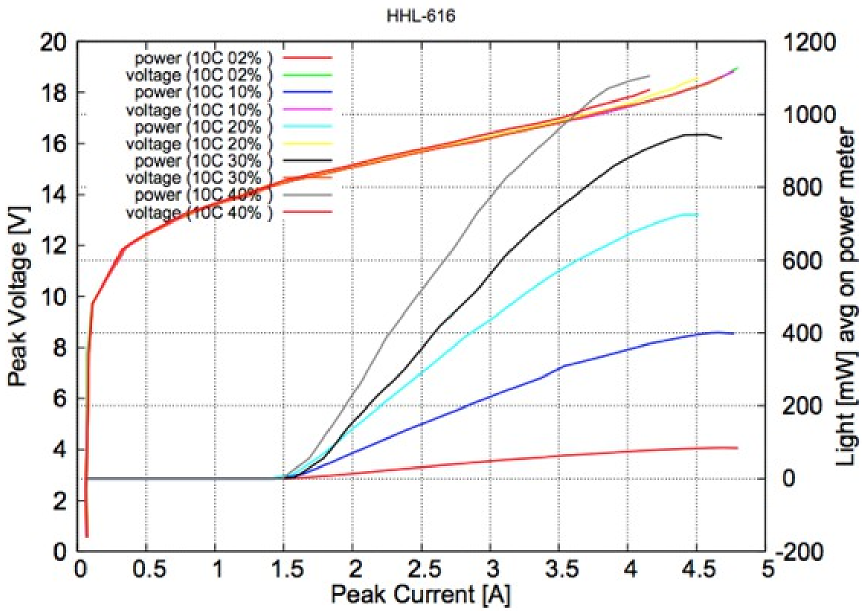
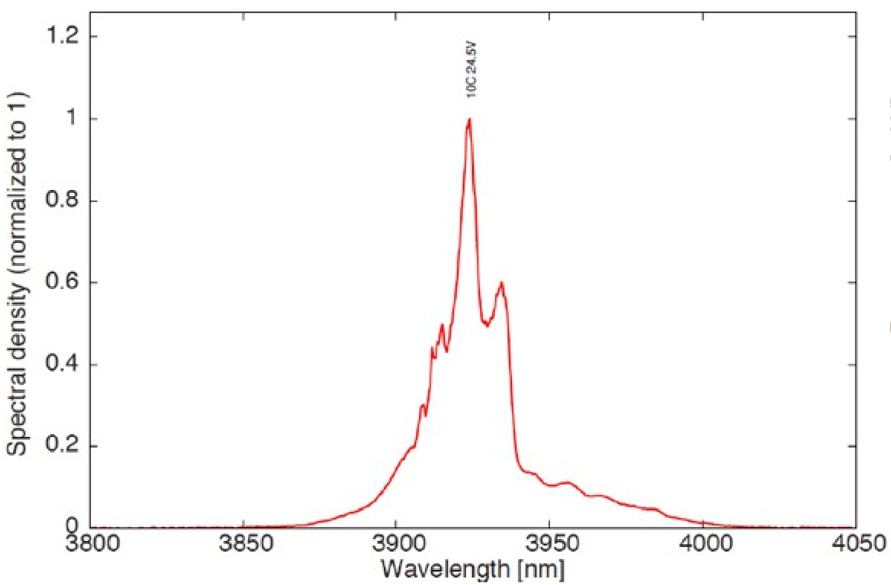
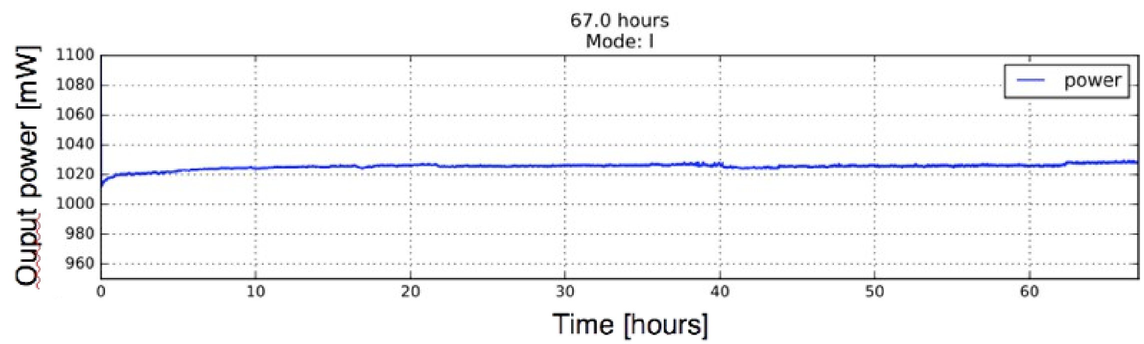
High power QCLs

4.0 µm QCL – package level performance



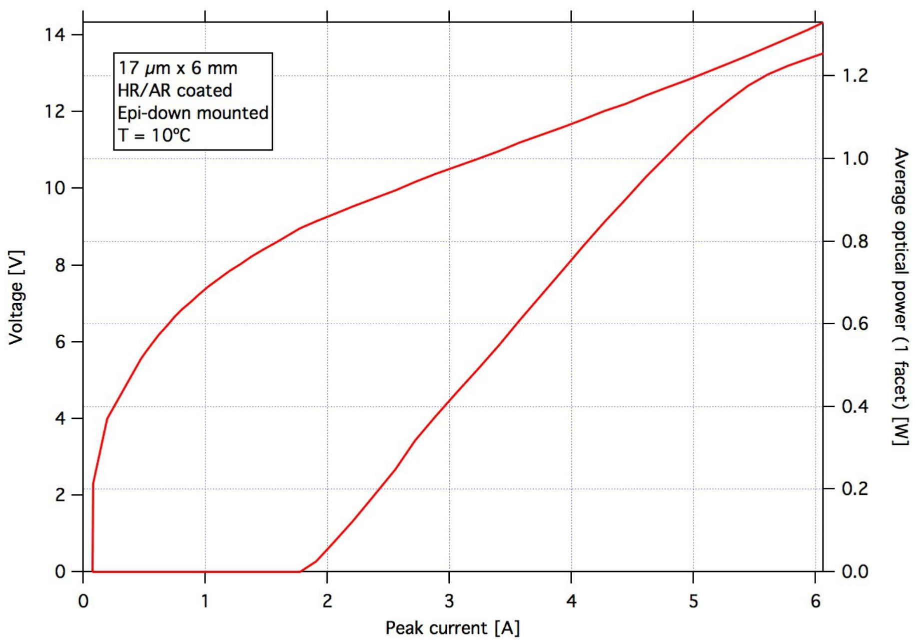
- T = 10°C
- >1 W average power at λ = 3.925 *µ*m
- Wall-plug efficiency = 5% at 10°C
- All units are burned in at full power before delivery

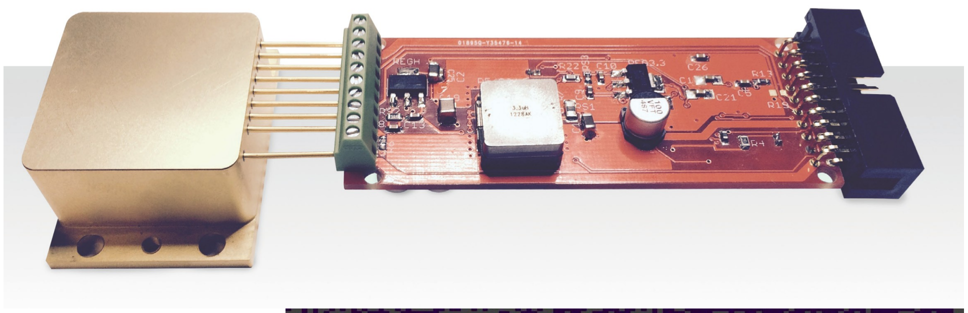


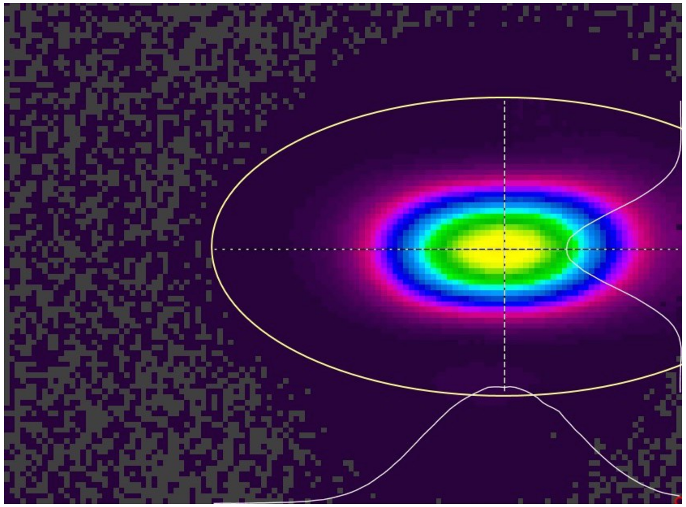


High power QCLs

9.7 µm QCL – package level performance







- λ = 9.7 μm
- Average power: 1.25 W at 40% duty-cycle, T = 10°C
- Beam divergence (full angle at 0.8 W): 7.4 x 3.7 mrad
- High beam quality

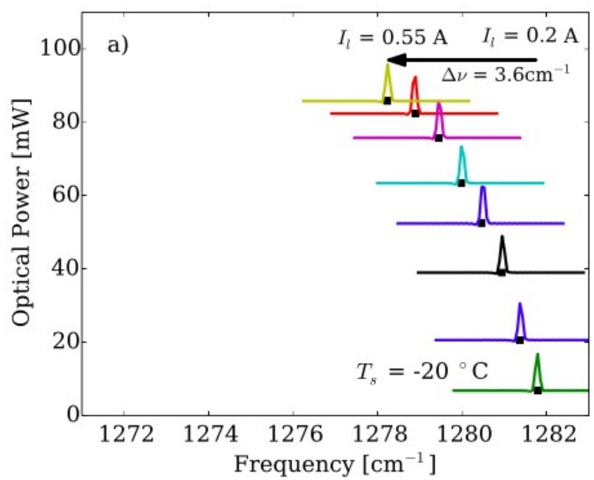
Integrated heater

QC-ET

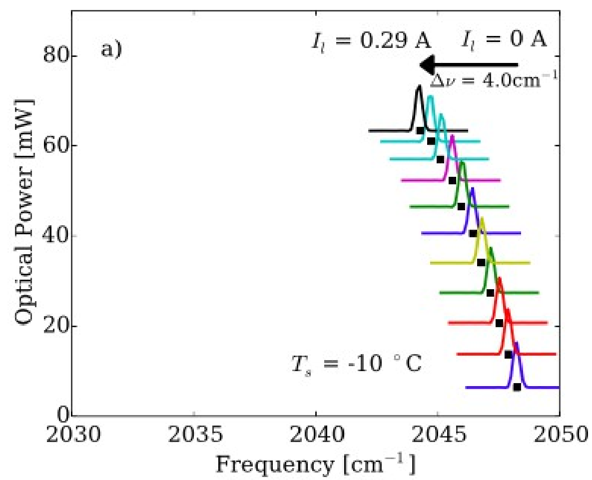
QCL Temperature tuning

Tuning with laser current

7.8 µm



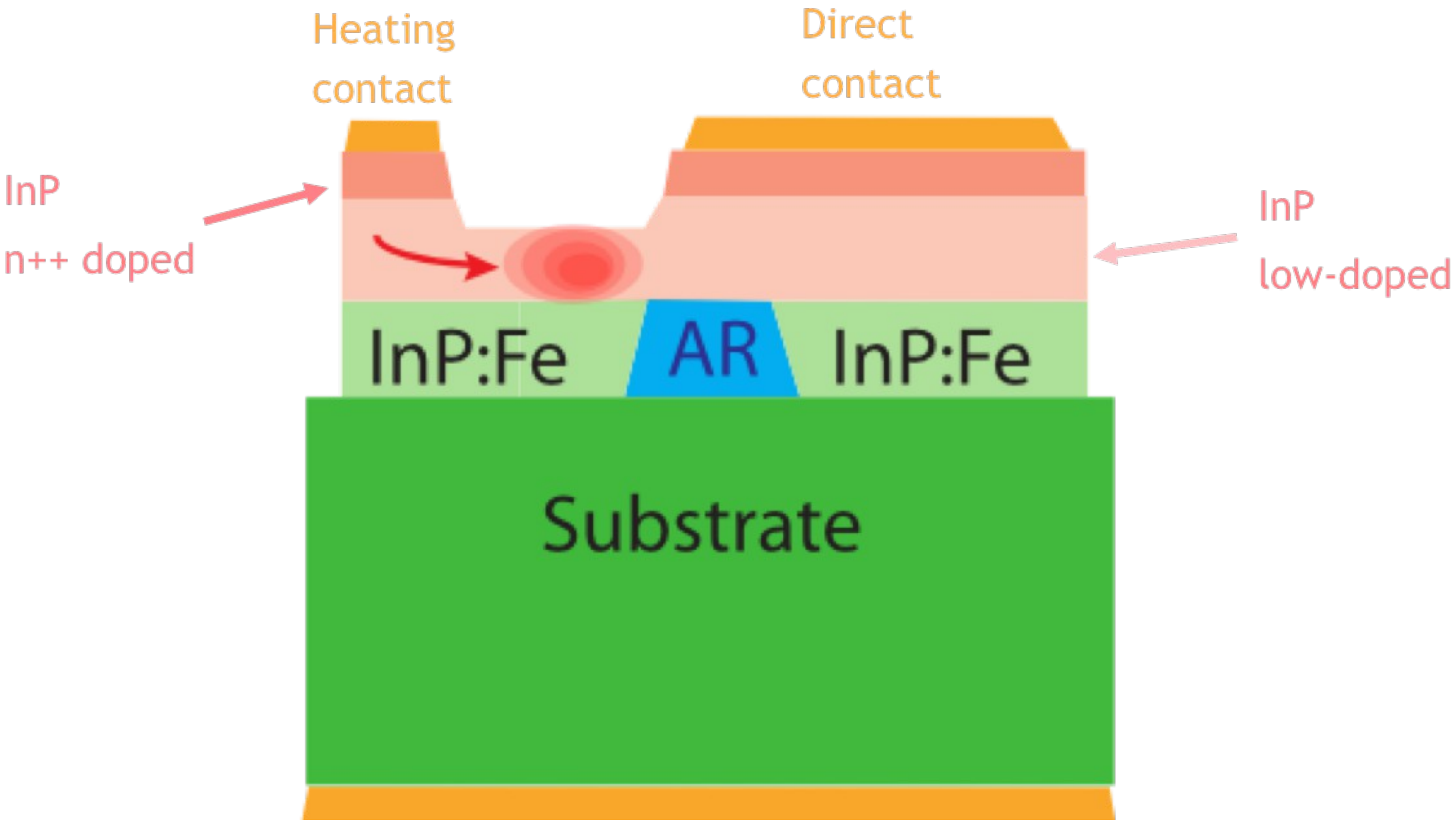
4.9 µm



Integrated heater

Core technical device characteristics

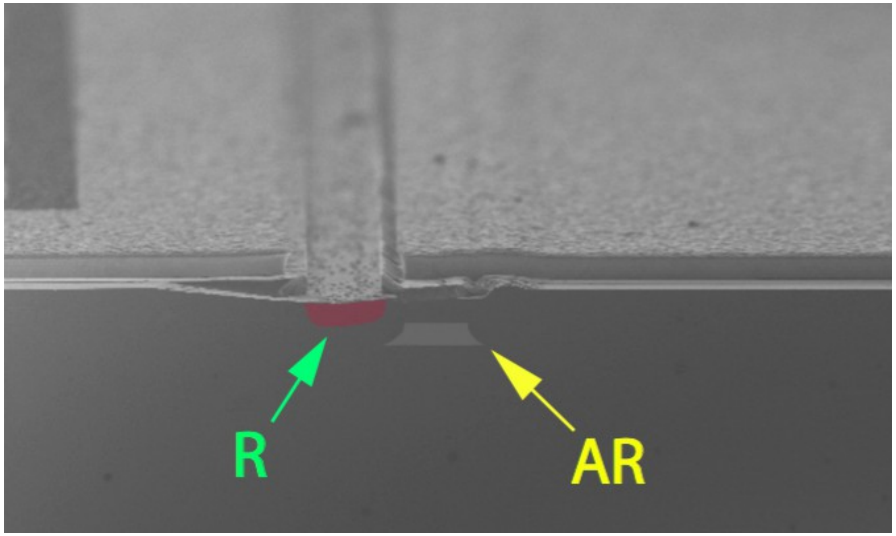
- New process developed
- Extended top contact for integrated circuiting

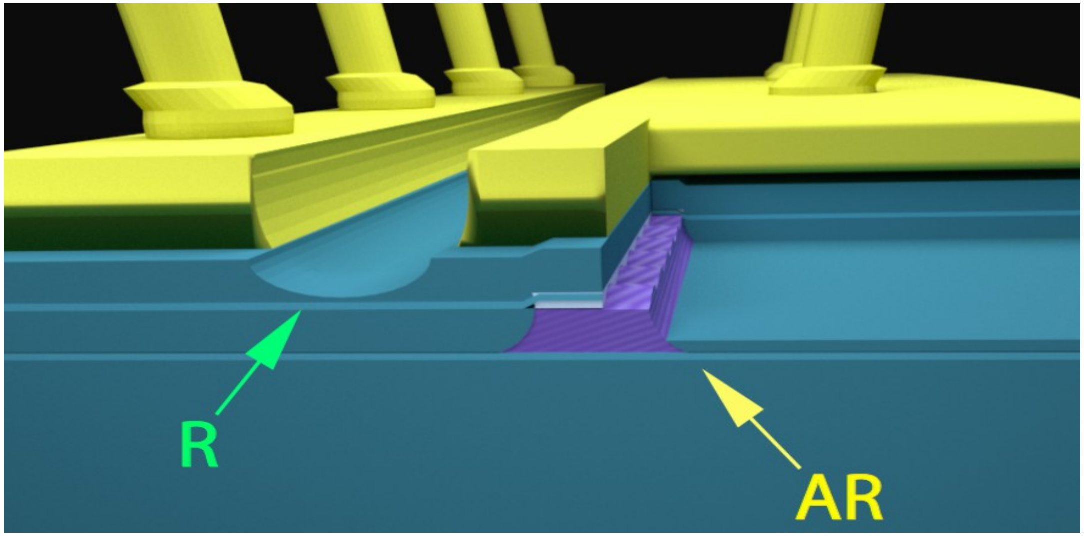


A. Bismuto et al., Opt. Exp. 23, 29715 (2015)
US Patent 2015078411 A1

Integrated heater

Core technical device characteristics





- Resistive heater close to the laser (<10 μm)
  - Fast modulation
  - High tuning efficiency (cm^{-1}/W)
- Independent power and wavelength controls

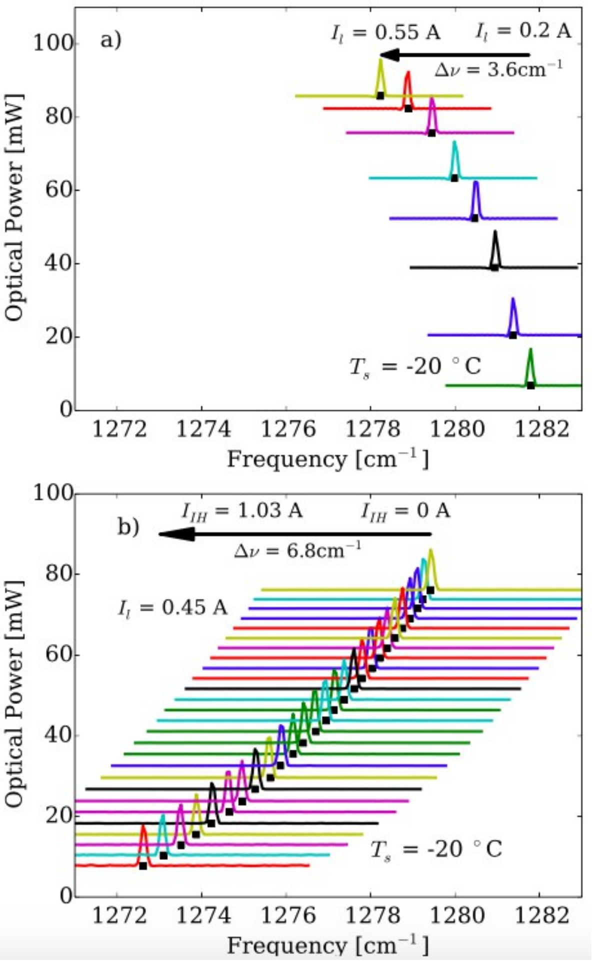
Integrated heater

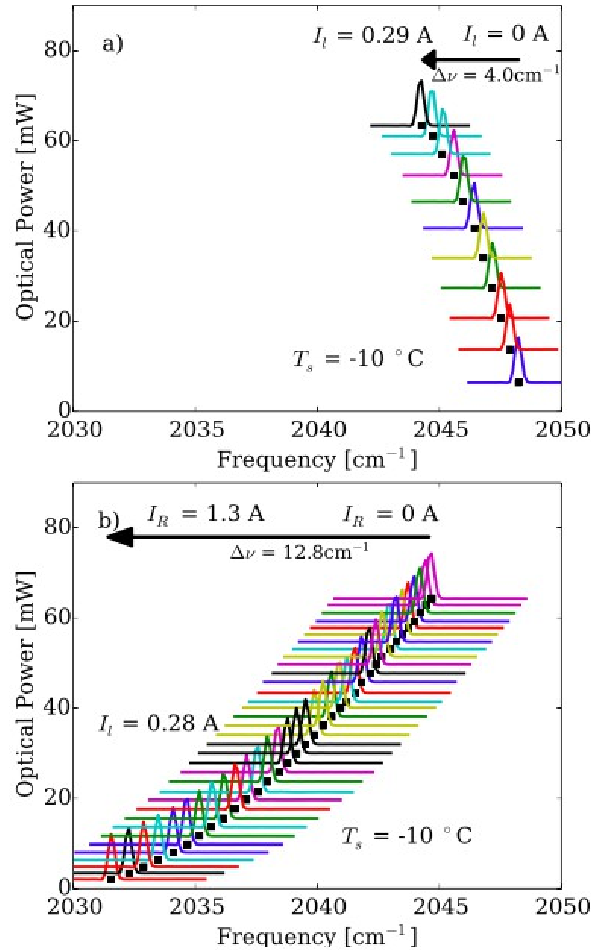
7.8 µm

4.9 µm

Tuning with laser current

Tuning with integrated heater

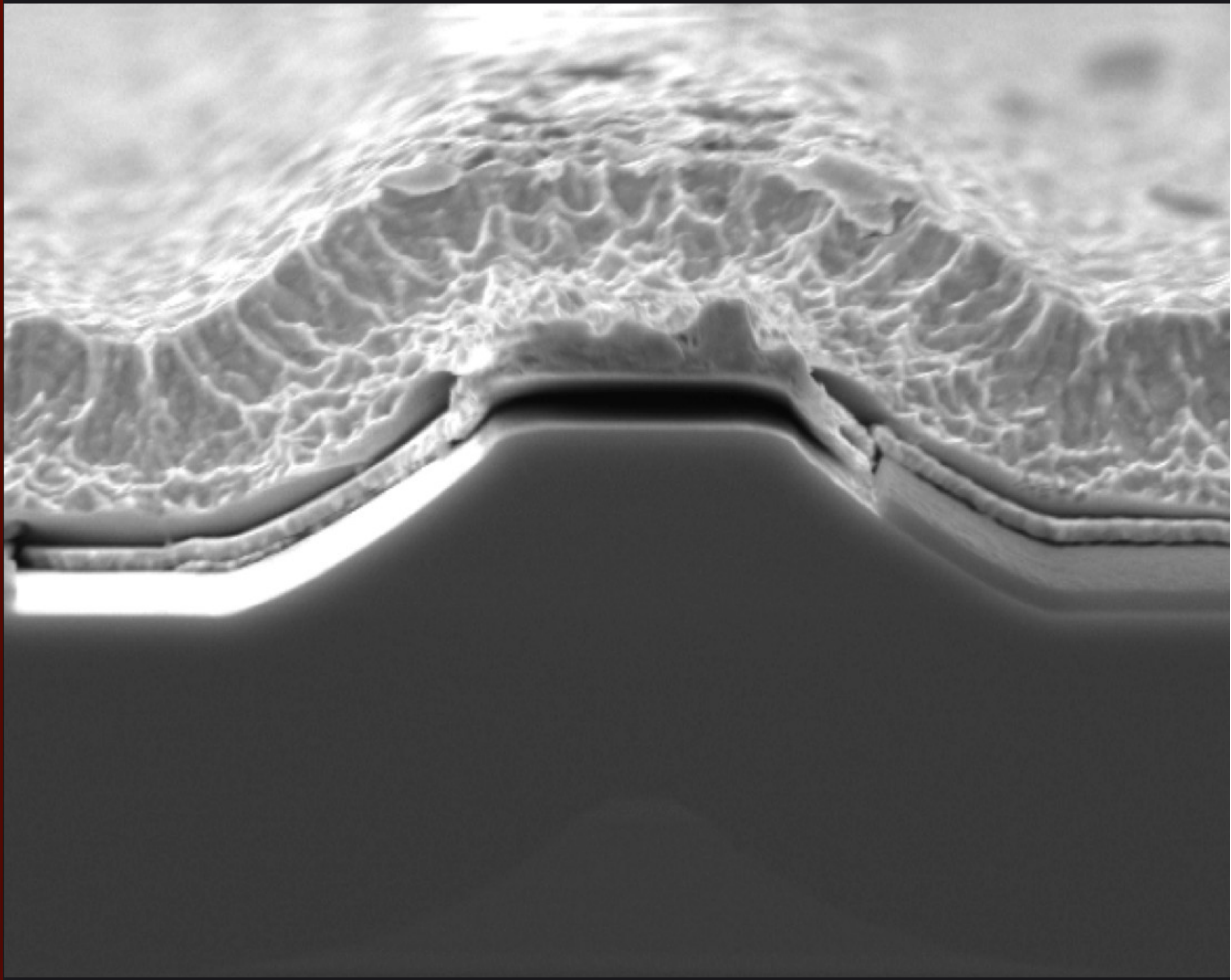




2-3 times increase in tuning range at constant heatsink temperature

QCLs based on Vernier effect

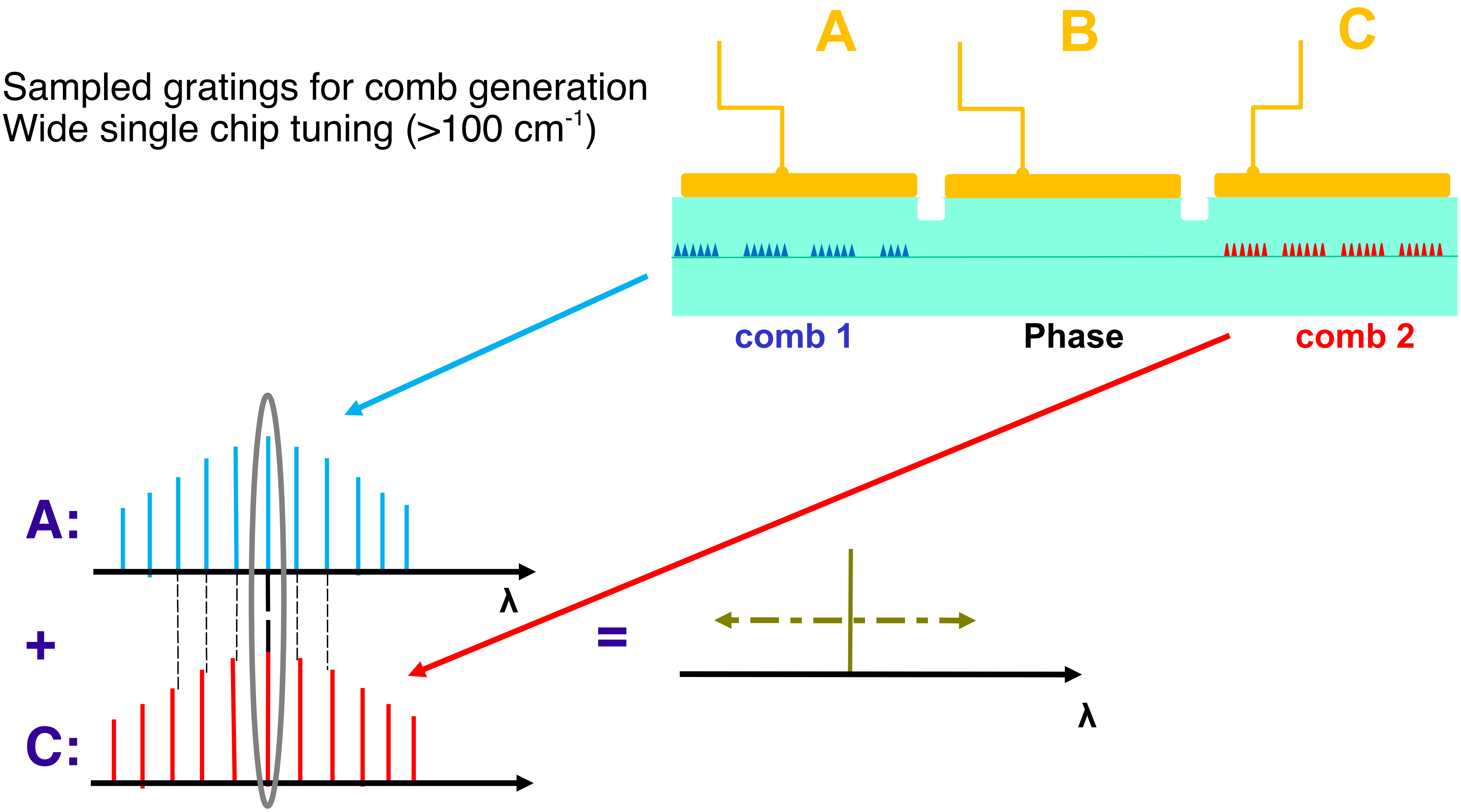
QC-XT



QCLs based on Vernier effect

Core technical device characteristics

Sampled gratings for comb generation
Wide single chip tuning (>100 cm^{-1})



QCLs based on Vernier effect

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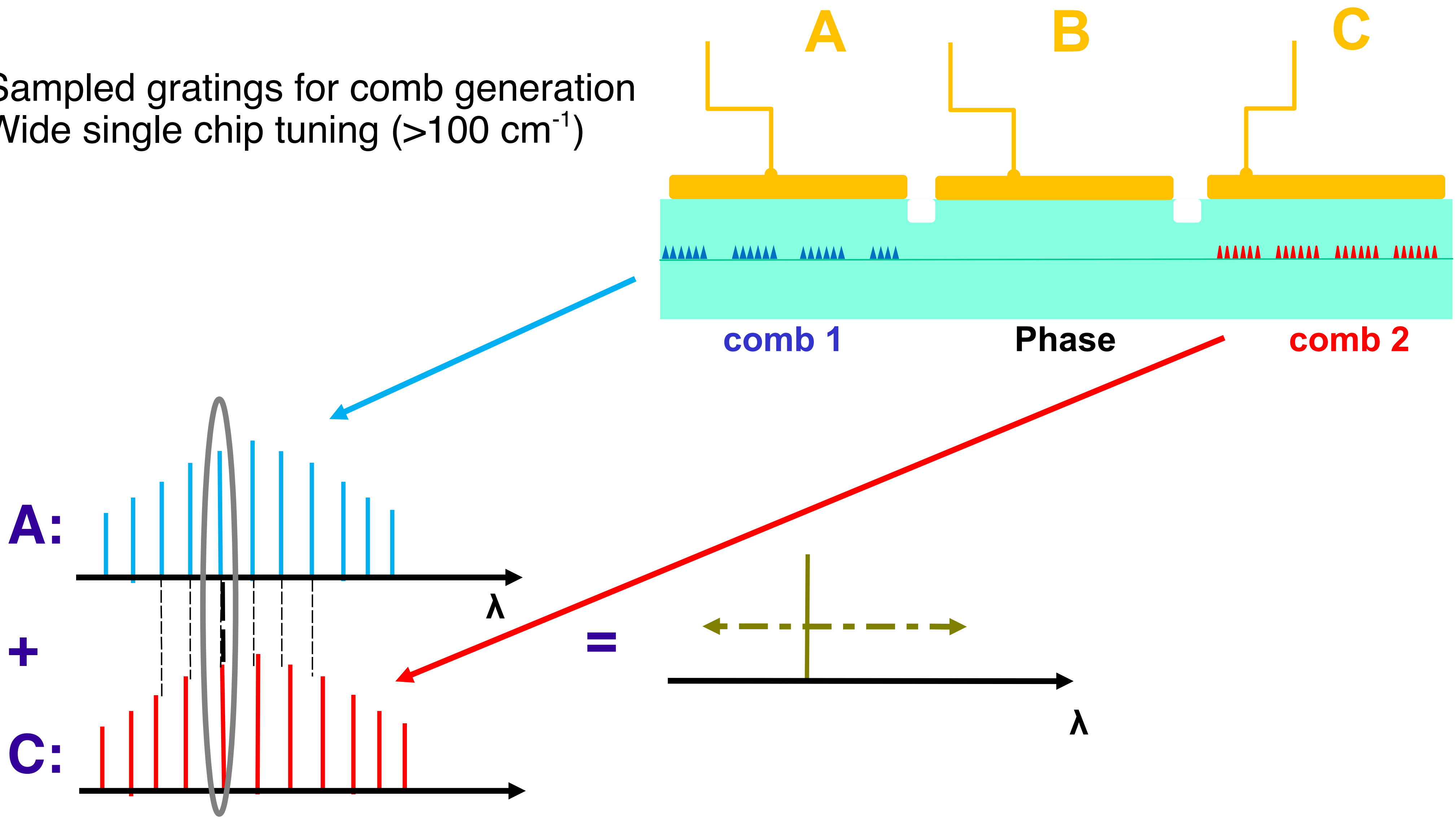

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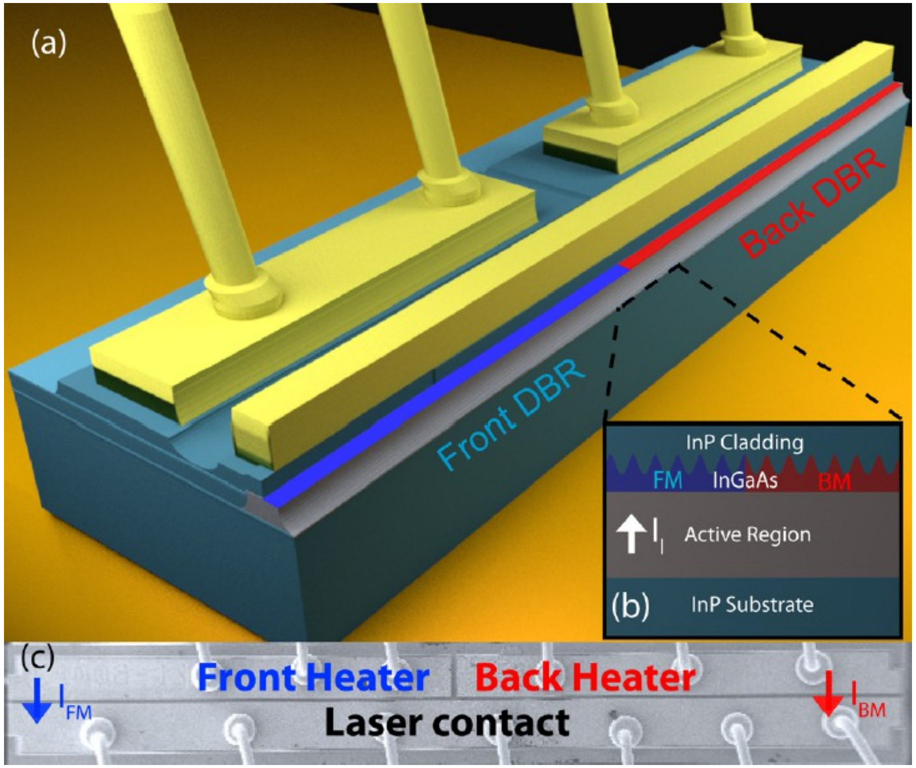
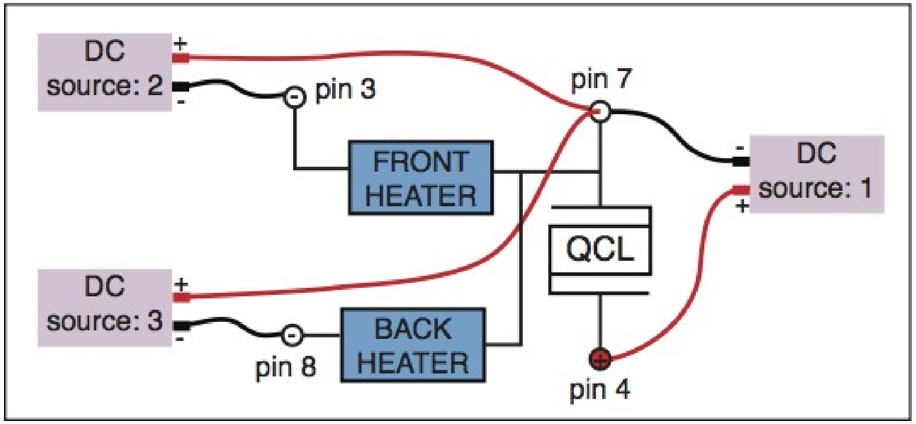
QCLs based on Vernier effect

Core technical device characteristics

- QC-XT Laser Sources are controlled by three independent current inputs.
- Two inputs control the front and back mirrors of the cavity ($\mathbf{I}_F$ and $\mathbf{I}_B$).The laser itself is driven by the laser current $\mathbf{I}_L$ and behaves as a normal DFB laser with the available range modified by the values of $\mathbf{I}_F$ and $\mathbf{I}_B$.
- Linewidth ~ 1 MHz like DFB lasers.



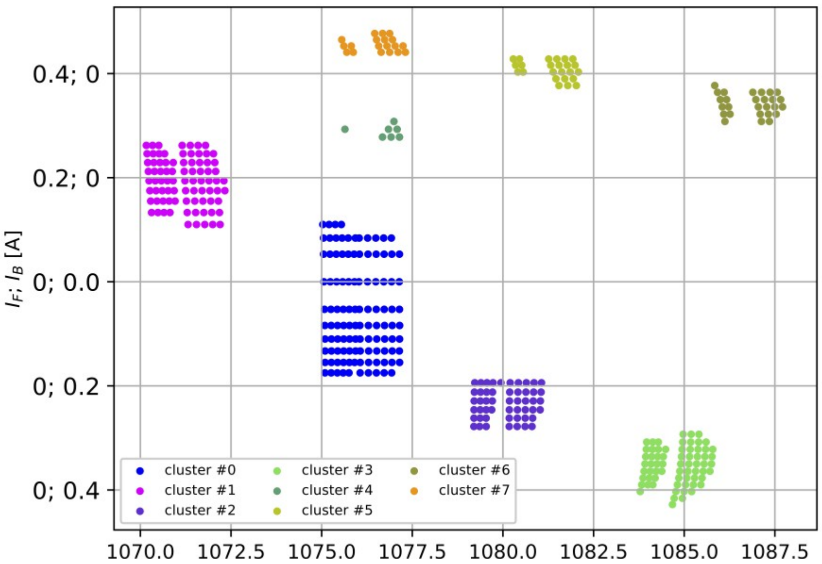


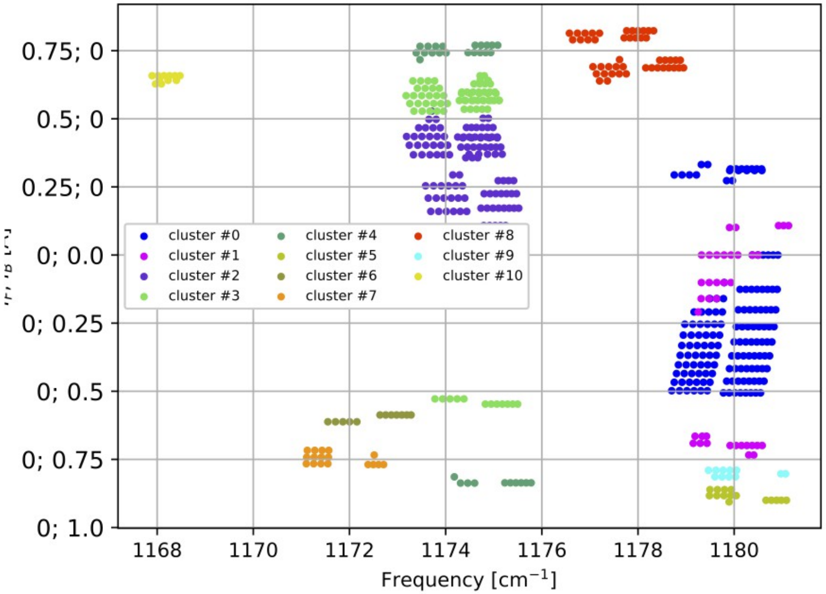
US Patent 9,209,600 B2
Y. Bidaux et al., APL 107, 221108 (2015)

QC-XT first generation

Laser performances

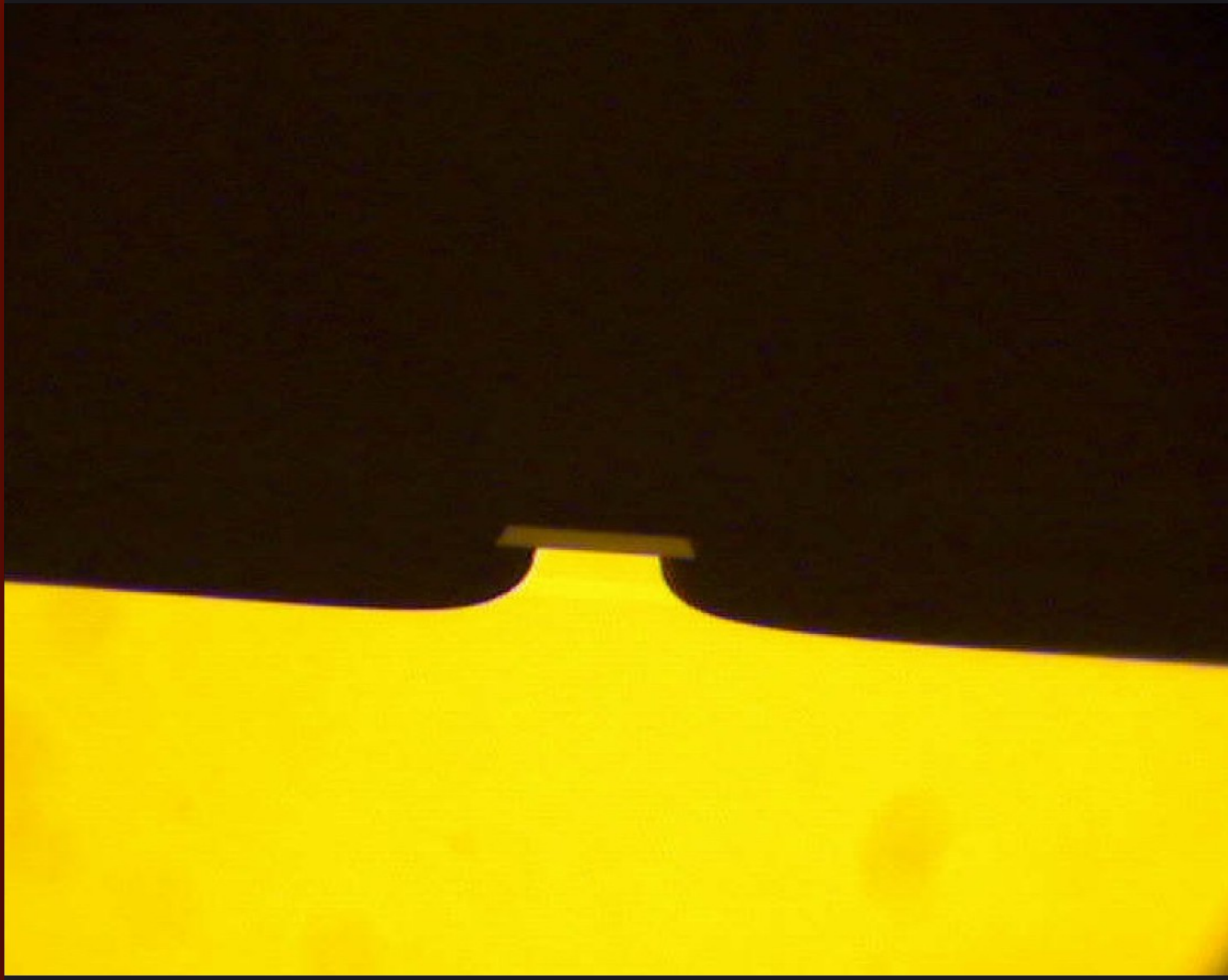
- Maps of single-mode region with continuous tuning zones.
- The laser can jump to any point within the map within < 1 ms.
- Each mode is defined by a triplet (doublet) of input currents at fixed temperature.
- Devices with large number of clusters (up to 9) demonstrated (R & D).
- However:
    - fabrication yield is an issue due to random phase of the cleaved facets
    - designed vs real clusters difficult to correlate
    - constant clusters gaps (SG)





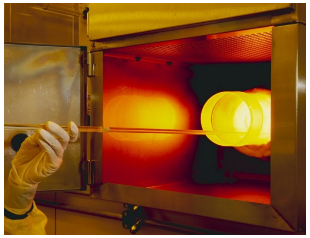
2nd generation of QC-XT

QC-XT

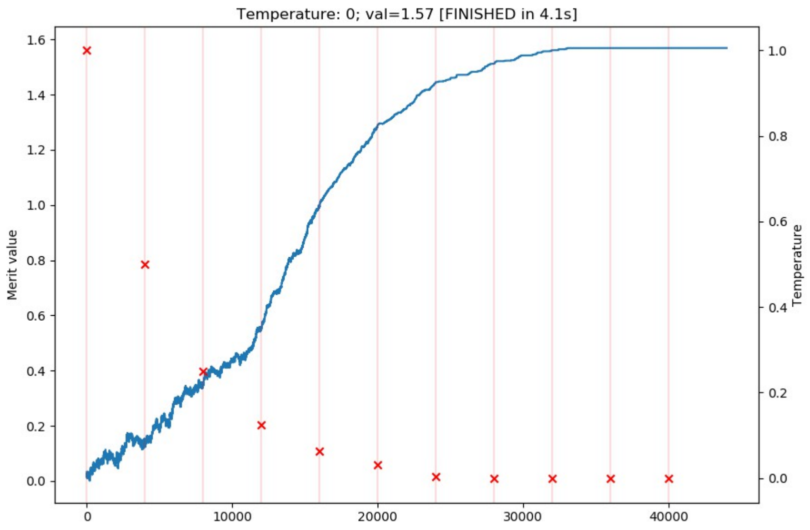


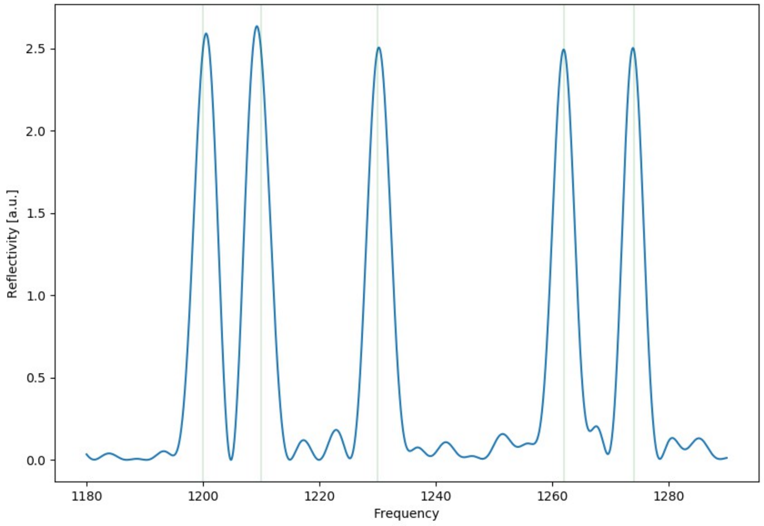
QC-XT 2nd generation

Core technical device characteristics



- Goals:
  - Number of clusters limited to 3-5
  - Wider gaps between clusters
  - Non-equidistant gaps
- Back and front DBR designed numerically by simulated annealing, inspired from metallurgy (AG)
- Etching profiles optimized considering the technological limitations (minimal structure size)
- Target frequencies selected for specific applications which can be non-equidistant on the contrary to first generation (SG)
- 2nd generation: AG and SG on same wafer

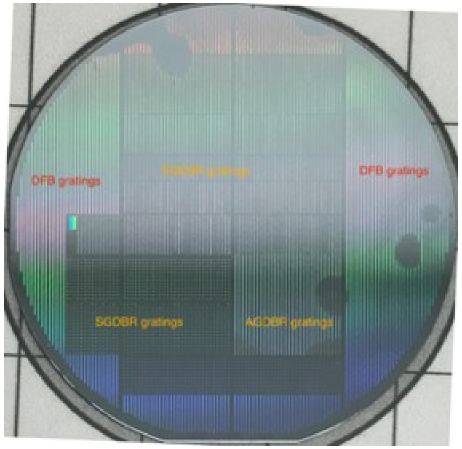


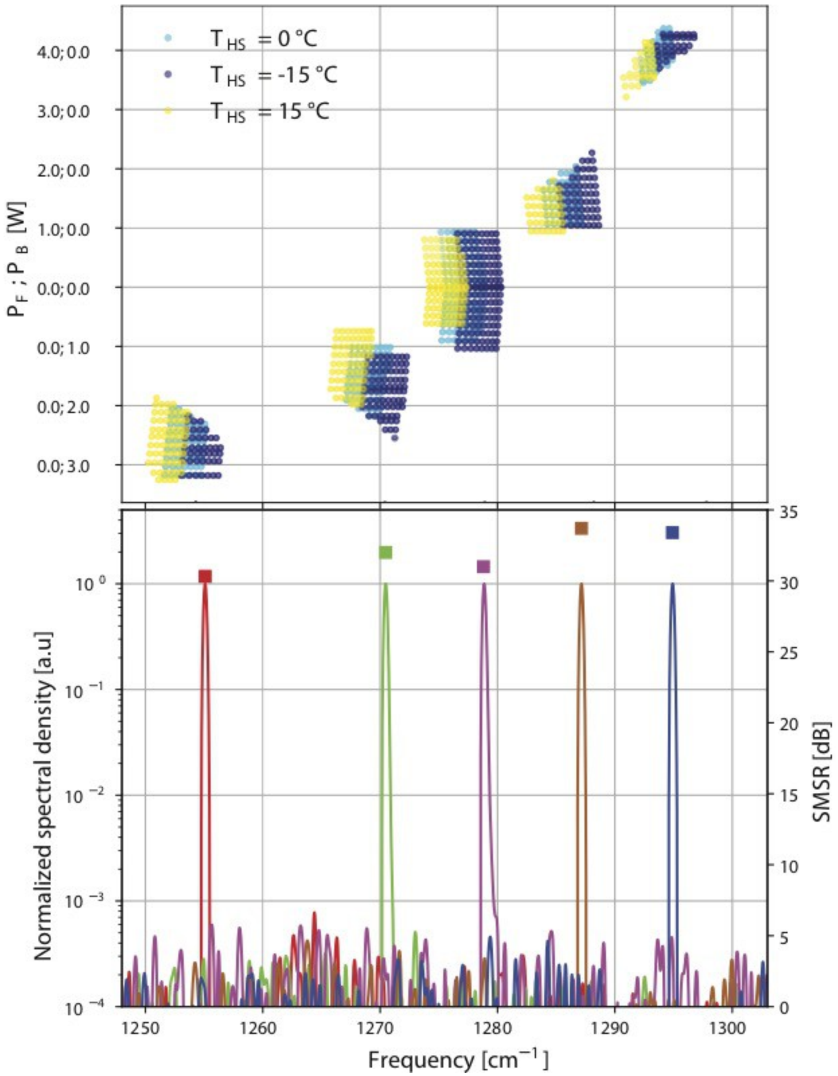


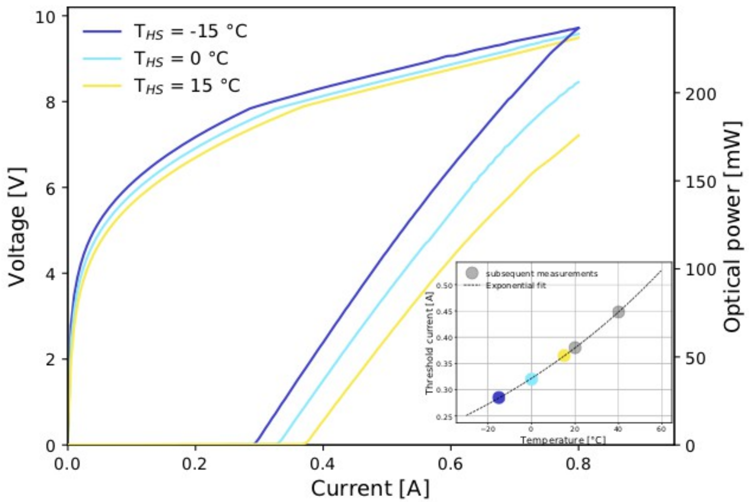
QC-XT 2nd generation

Laser performances ~1280cm^{-1}

- Design: limited to 3- 5 clusters with broader gaps
- Very high CW power (> 200mW)
- 5 clusters lasers (AG)
  - Gaps up to >10cm^{-1}
  - Same amplitude for all reflectivity peaks
  - Very stable in clusters







Application: WaterSpy project

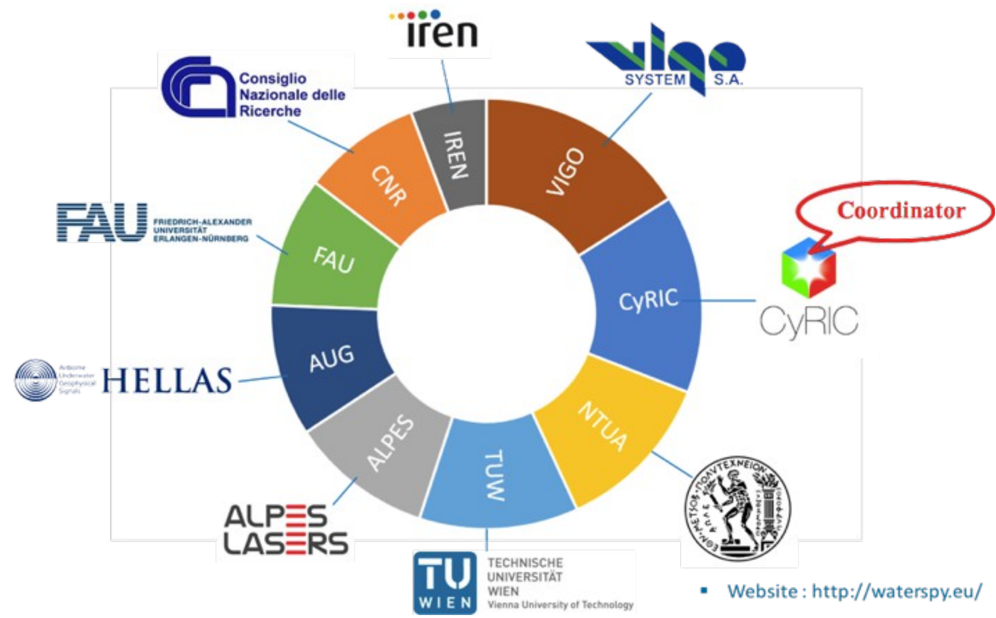
EU project

- **Aim** of the **WaterSpy** team: to develop a device that will require a couple of hours for a full water sample analysis of **100 mL**, in search for three heterotrophic bacterial cells (*E.coli, Salmonella and P.aerruginosa*).

Escherichia coli

Salmonella enterica

Pseudomonas aerruginosa



- In line with the EC and national regulations that require that no bacteria should be present in a sample of 100 mL of drinkable water.
- WaterSpy is taking advantage of advances in cutting edge photonic devices, in order to provide new capabilities in water analysis.

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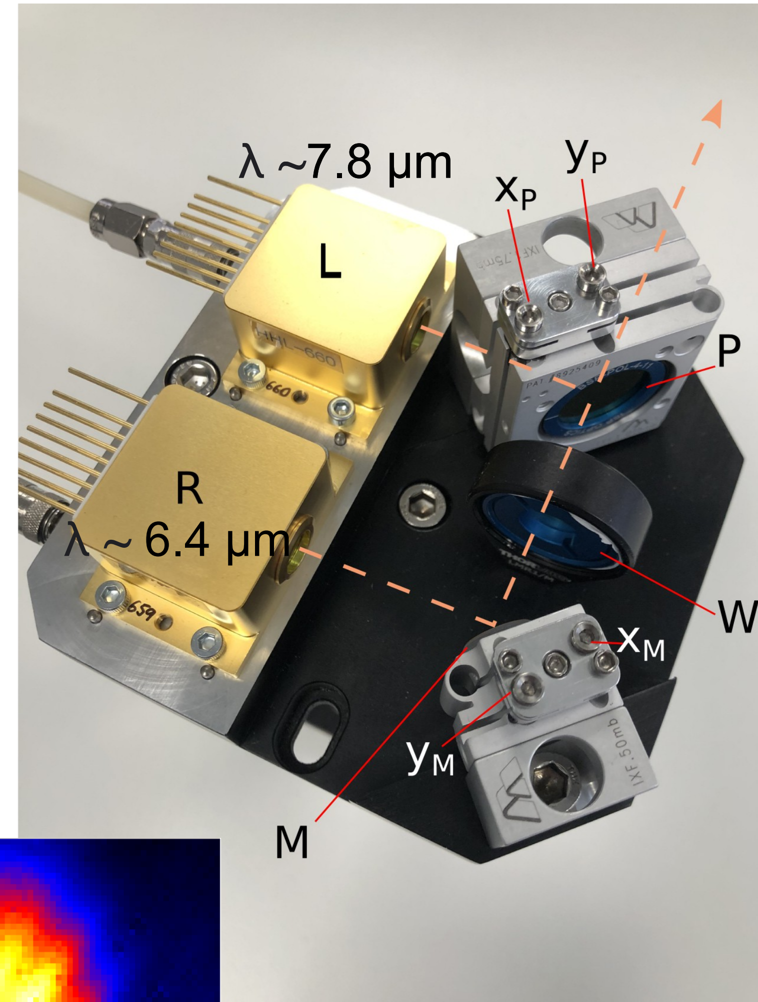
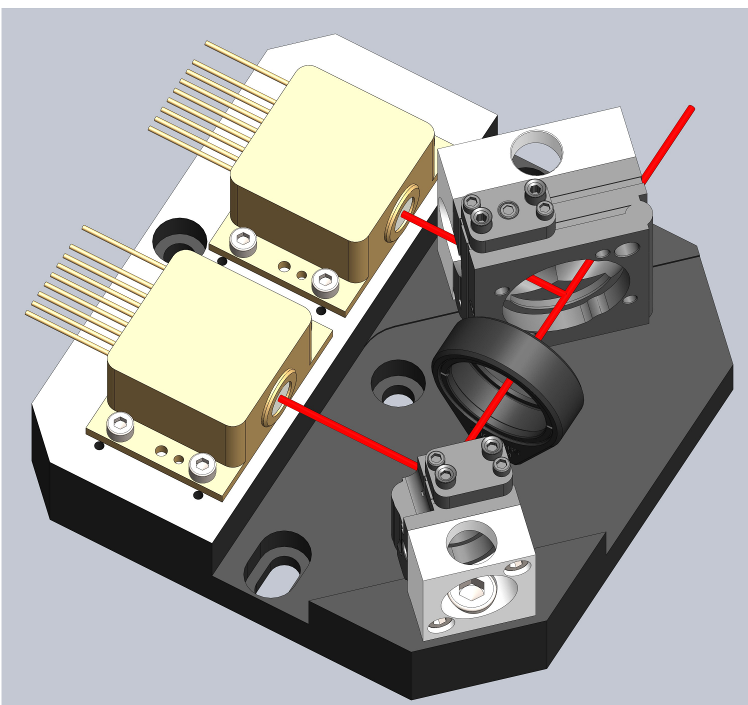
QC-XT 2nd generation

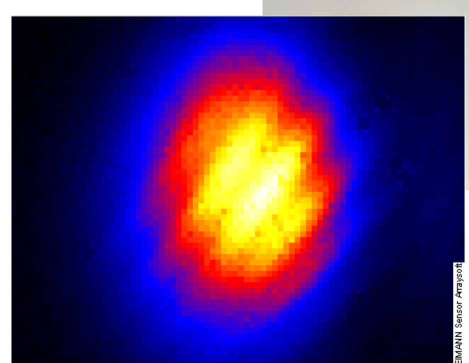
Beam combining

- Beam combining using
  - mirror (M)
  - half-wave plate (W)
  - polarizer (P)

- Good beam quality at the exit (FF at 1m)







Acknowledgments

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Thank You

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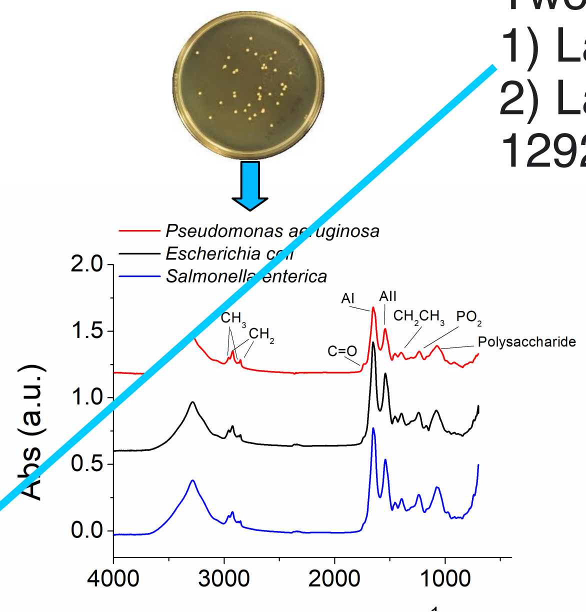
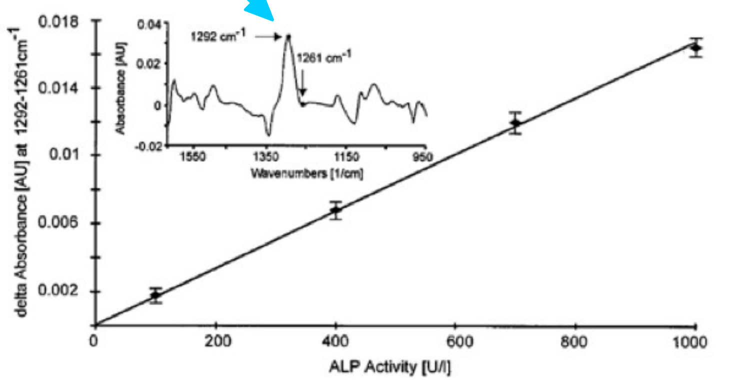
WaterSpy project

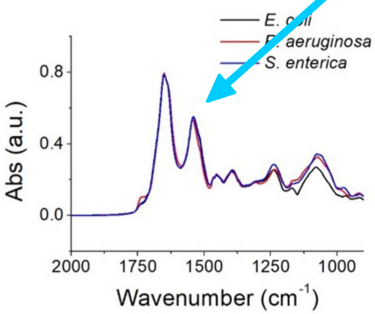
EU project

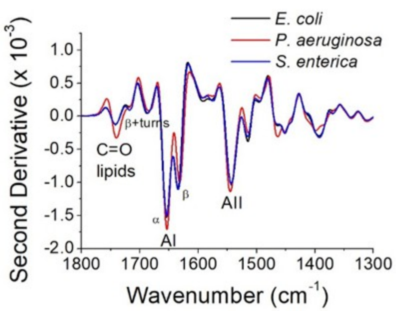
Bacteria could be identified through their **FT-IR bands**.

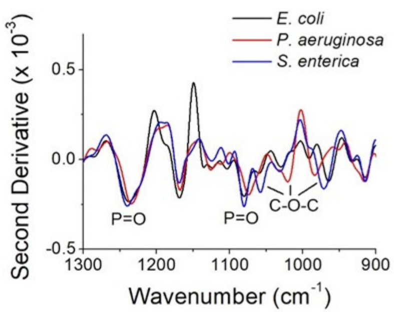
Two lasers to be fabricated:
1) Laser for amide II band around 1560cm^{-1}
2) Laser for catalytic reaction at 1261cm^{-1} + 1292cm^{-1}











QC-XT 2nd generation

Laser performances ~1280cm^{-1}

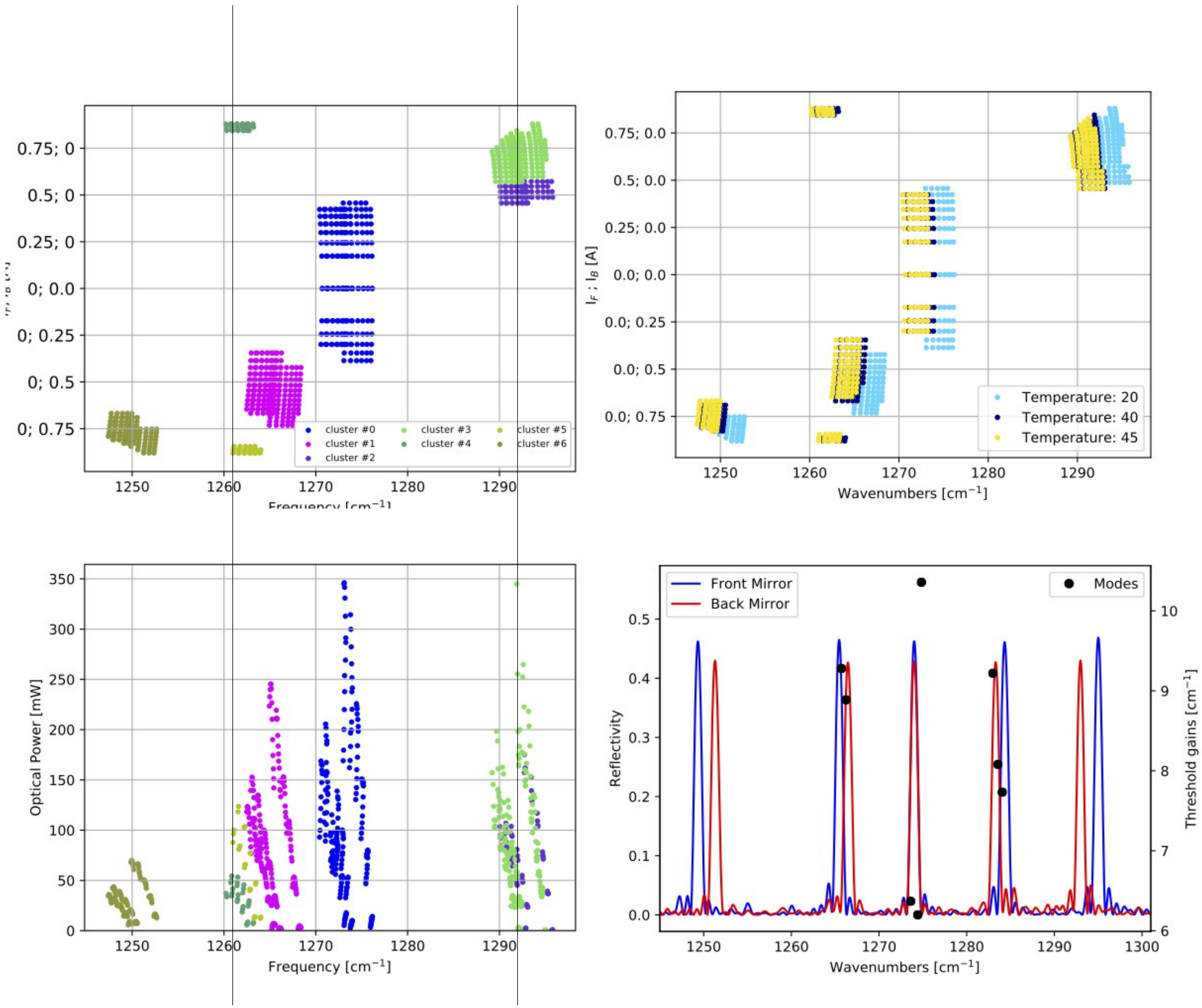
- WaterSpy needs
  - 1261cm^{-1}
  - 1292cm^{-1}

- Packaged laser (HHL)
- Both λ reached at 40-45C (same temperature important)

- 5 clusters laser (AG)
  - Good correlation with design
  - 1 cluster is missing

Cluster	I_B [A]	V_B [V]	I_F [A]	V_F [V]	I_L [A]	V_L [V]	Freq [cm^{-1}]	T [C]	P_{opt} [mW]
#0-Back	0.00 - 0.44	0.0 - 1.7	0	0	0.36 - 0.80	7.9 - 9.7	1270.9 - 1278.0	0 - 50	211
#0-Front	0	0	0.00 - 0.40	0.0 - 1.6	0.36 - 0.80	7.9 - 9.7	1270.8 - 1278.0	0 - 50	168
#1-Front	0	0	0.40 - 0.60	1.6 - 2.2	0.36 - 0.80	7.8 - 9.5	1290.5 - 1297.7	0 - 50	121
#2-Front	0	0	0.51 - 0.88	2.0 - 3.5	0.47 - 0.80	8.0 - 9.4	1289.4 - 1296.4	0 - 50	181
#3-Back	0.36 - 0.76	1.4 - 3.2	0	0	0.36 - 0.80	7.7 - 9.5	1262.8 - 1270.1	0 - 50	170
#4-Back	0.80 - 0.88	3.7 - 4.1	0	0	0.59 - 0.80	8.2 - 9.0	1261.1 - 1263.3	40 - 50	56
#4-Front	0	0	0.76 - 0.88	3.3 - 3.9	0.54 - 0.80	8.1 - 9.1	1260.4 - 1264.7	20 - 50	55
#5-Back	0.62 - 0.88	2.7 - 3.8	0	0	0.47 - 0.80	8.0 - 9.3	1247.6 - 1254.2	0 - 50	73

Table 1: Overview of the clusters.



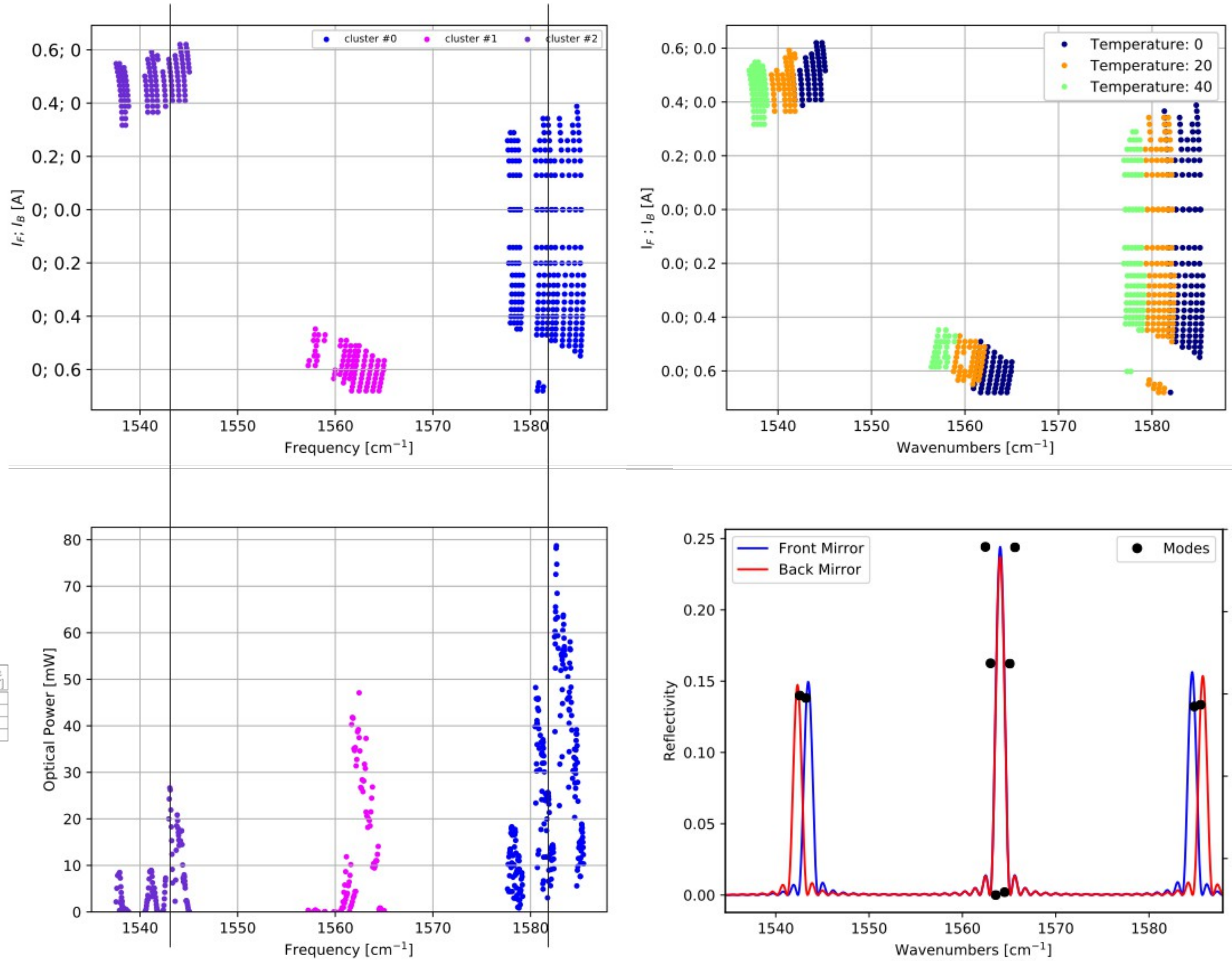
QC-XT 2nd generation

Laser performances ~1560cm^{-1}

- WaterSpy needs:~1545 + 1580cm^{-1} (broad feature)
- Both λ reached at 0-40C
- 3 clusters laser (SG)
  - Very good correlation with design
  - Gap ~ 21cm^{-1}

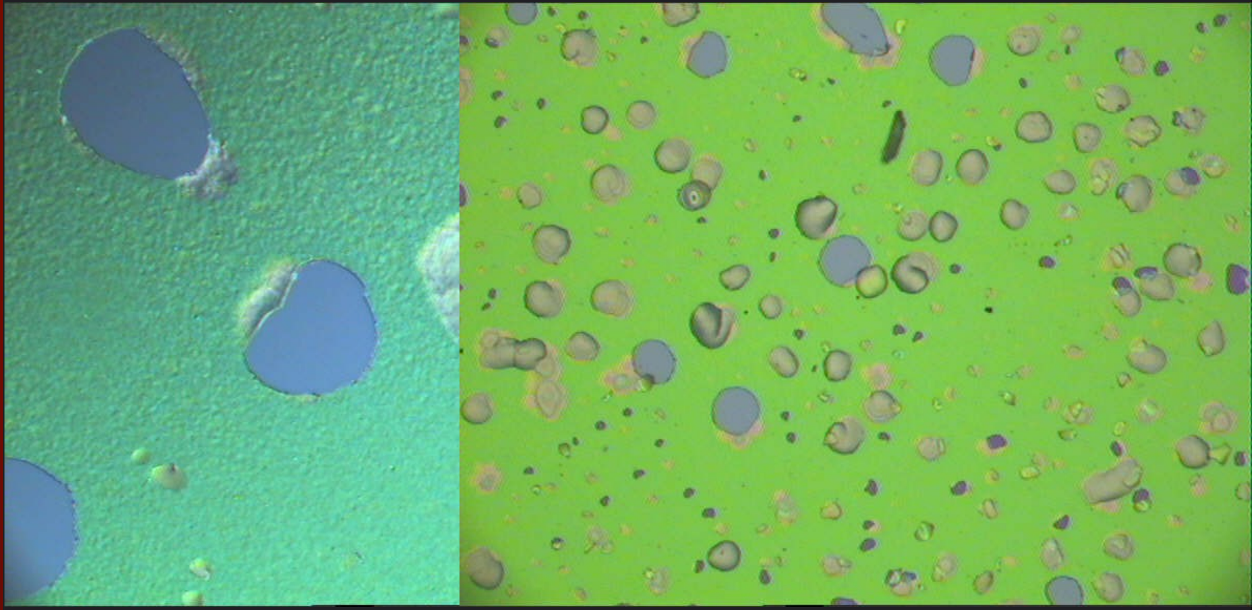
Cluster	I_B [A]	V_B [V]	I_F [A]	V_F [V]	I_L [A]	V_L [V]	Freq [cm^{-1}]	T [C]	P_{opt} [mW]
#0-Back	0.00 - 0.68	0.0 - 3.1	0	0	0.36 - 0.54	10.8 - 12.5	1577.8 - 1585.4	0 - 40	79
#0-Front	0	0	0.00 - 0.39	0.0 - 1.6	0.36 - 0.54	11.0 - 12.5	1577.6 - 1585.2	0 - 40	65
#1-Back	0.45 - 0.68	2.0 - 3.0	0	0	0.36 - 0.54	10.6 - 12.1	1557.2 - 1565.0	0 - 40	47
#2-Front	0	0	0.32 - 0.62	1.3 - 2.6	0.36 - 0.54	10.7 - 12.2	1537.6 - 1545.1	0 - 40	27

Table 1: Overview of the clusters.



Ruggedized packaging

HP-QCL



Ruggedized packaging development

Ruggedized packaging

Design:

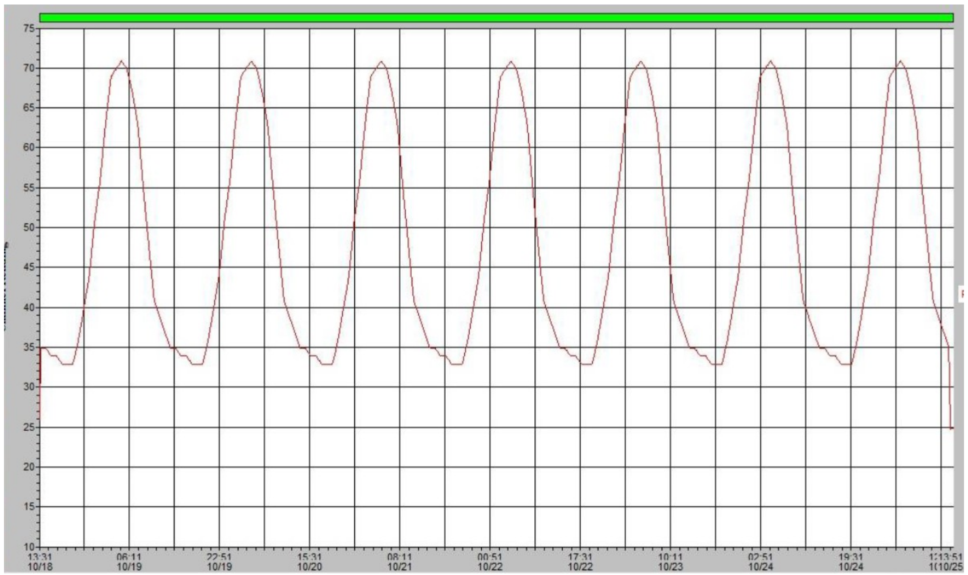
- Numerical simulations of environmental conditions using finite element method (laser package + driver)
- Calculation of safety margins

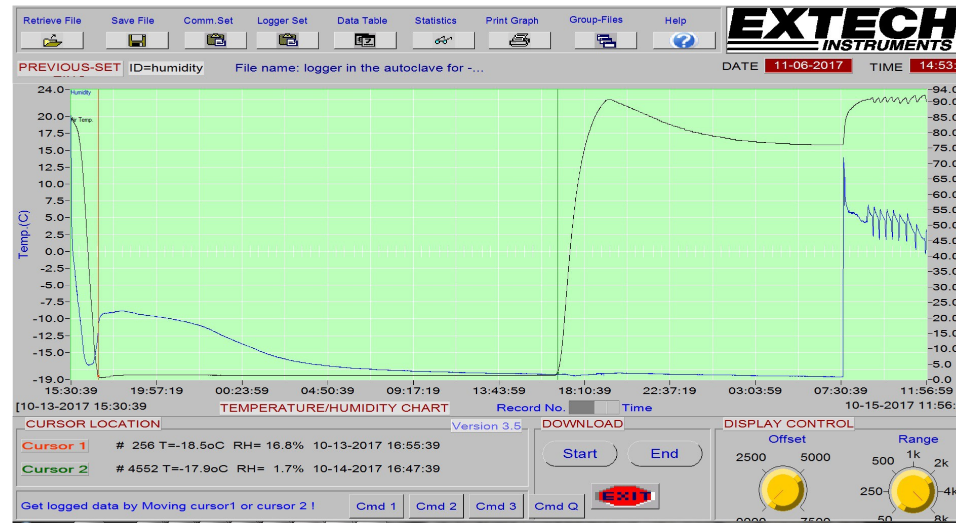
Experimental validation:

- Proof of design with a set of 6 lasers + 6 drivers:
  - 4x MW QCLs: 1 W average at 4.0 μm
  - 2x LW QCLs: 1 W average at 9.7 μm

Temperature cycle tests

Ruggedized packaging





High temperature cycles:

- 7 cycles of 24h up to 71°C
- Per MIL-STD 810F, method 501.4, Procedure I

Low temperature cycles:

- 1 cycle of 24h down to -20°C
- Per MIL-STD 810F, method 502.4, Procedure I

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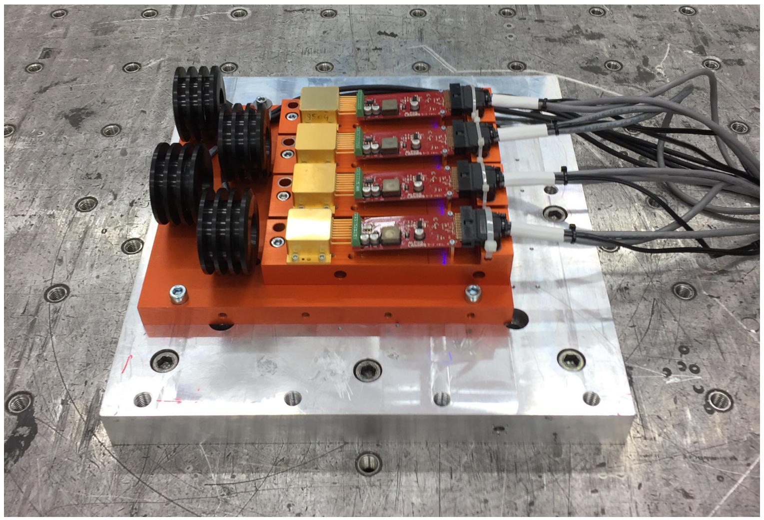
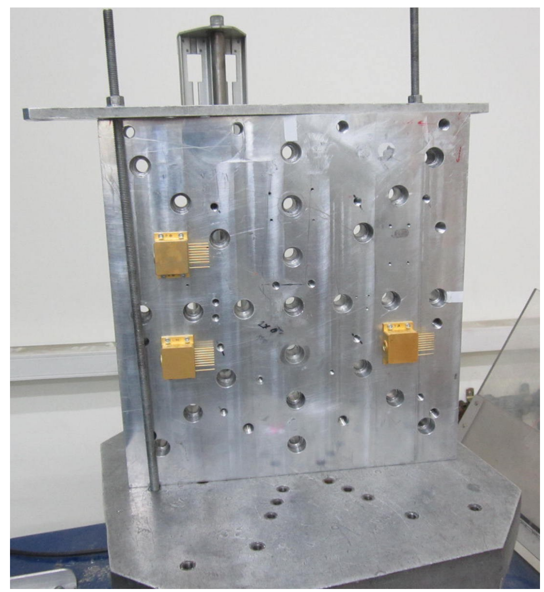
Vibration / shock tests

Ruggedized packaging



Vibration tests:

- Per MIL-STD 810F, Figure 514.5C-17
- 0.04 g^2/Hz from 20 Hz to 1 kHz
- 1 hour per axis

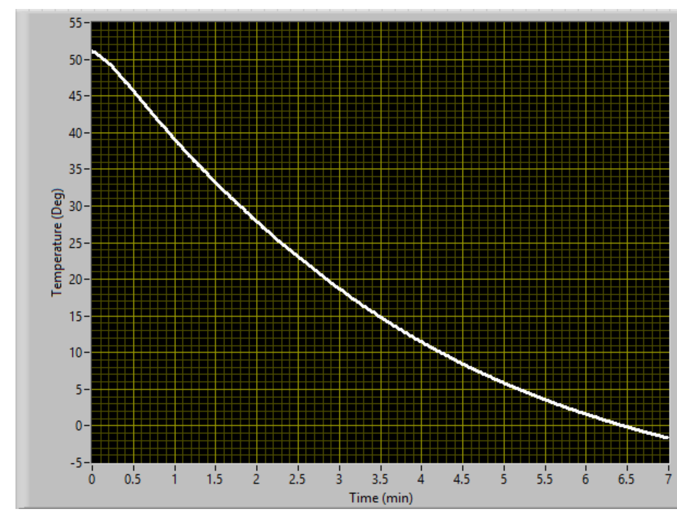


Shock tests:

- Per MIL-STD 810F, Method 516.5, procedure I
- Half sine, 85 g, 5 ms
- 3 axes, 6 shocks per axis

Temperature shock tests:

- Per MIL-STD 810F, Method 503.4, procedure II
- Cooling down form 55°C to 0°C at a rate of ≥ 11°C/min



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Ruggedized packaging specifications

Proof of design results

- Beam pointing and divergence:

✓ Beam pointing precision and retention: ±0.5 mrad
✓ Beam divergence precision and retention: ±10% of divergence

- Environmental conditions:

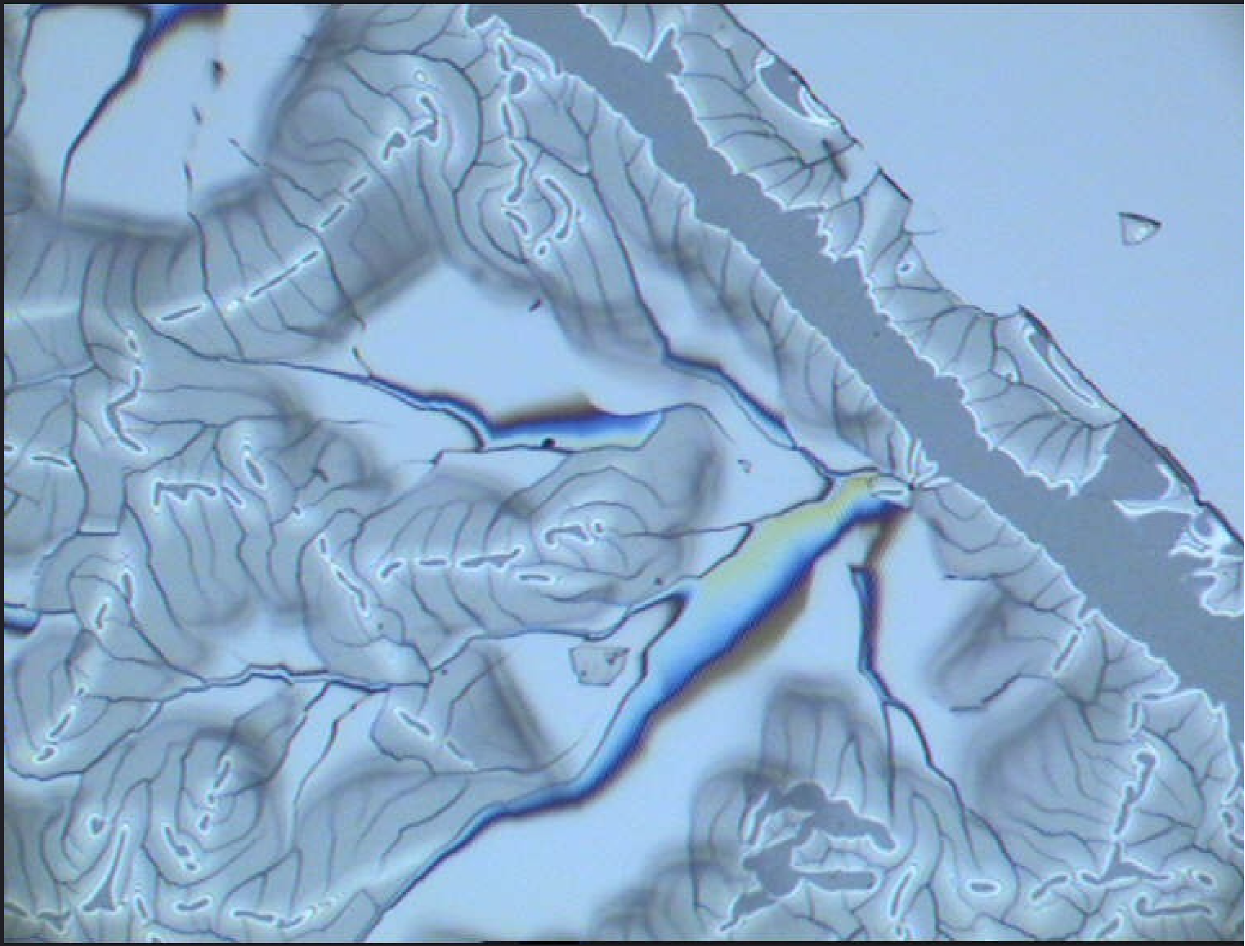
✓ Internal temperature (operating): 0°C to 25°C
✓ Heatsink temperature (operating): 0°C to 35°C
✓ Ambient temperature* (operating): -20°C to +71°C
✓ Storage temperature (non-operating): -20°C to +71°C
✓ Thermal shock: +55°C to 0°C, rate = 11°C
✓ Vibrations: 0.04 g^2/Hz, from 20 Hz to 2 kHz, 1 hour per axis
✓ Mechanical shocks: 85 g, 5 ms, half-sine profile, 6 shocks per axis

Met for the packaged laser and electronics driver

*Air temperature with laser mounted on heatsink

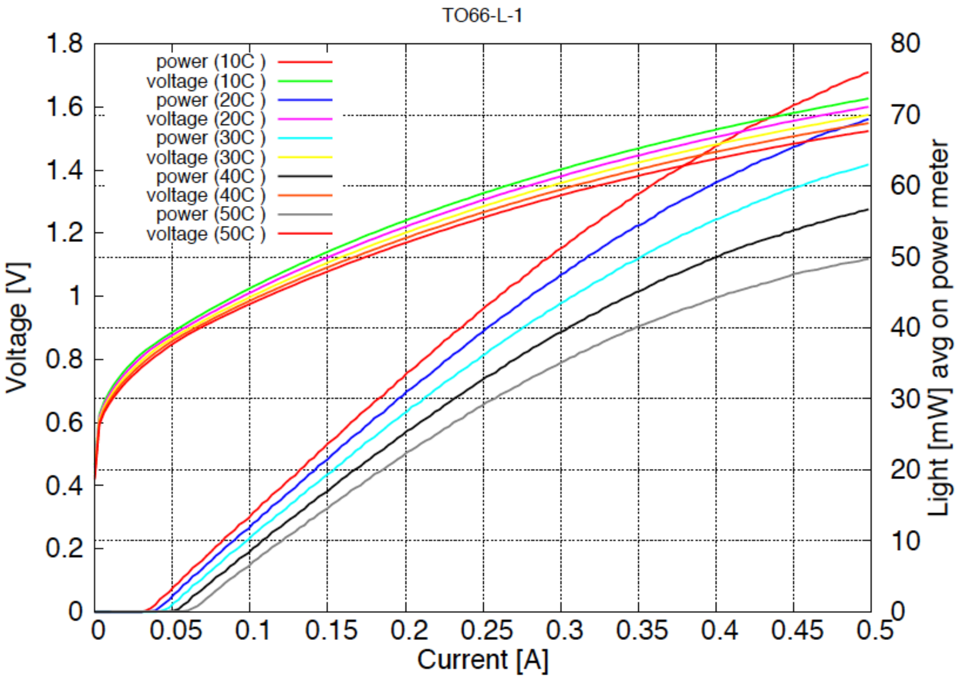
NEW: SWIR diode lasers

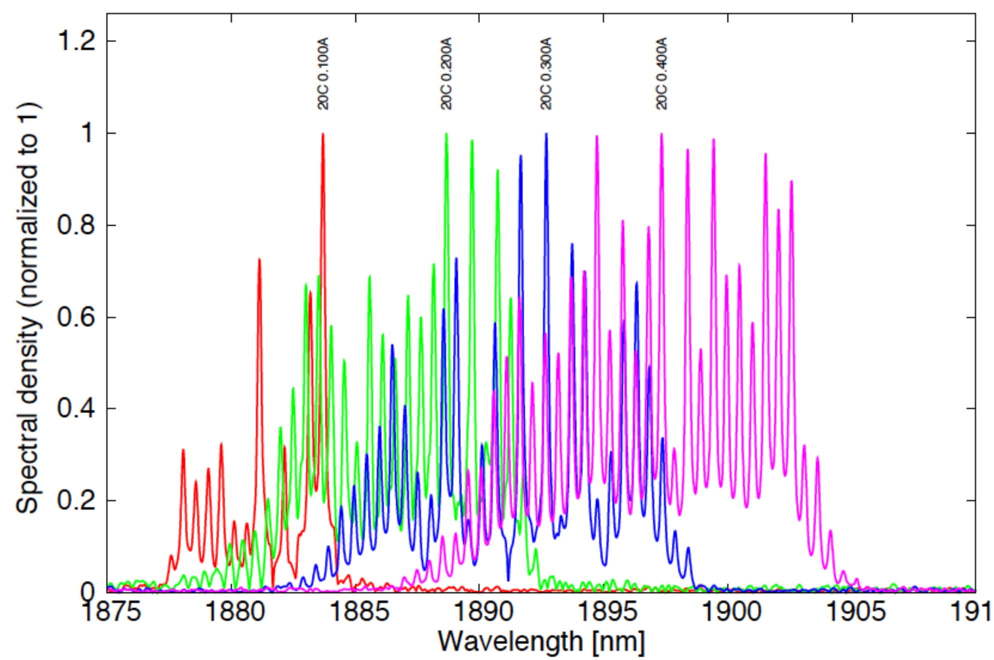
FP-LD



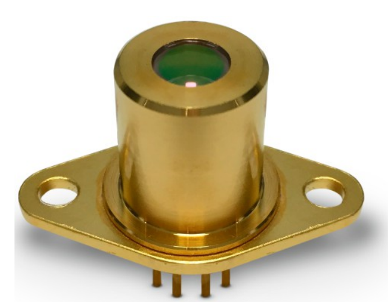
Short-wave infrared InP diode lasers

Laser performances





- Continuous-wave operation in TO66 package
- T = 10°C – 50°C
- P > 50mW
- Wavelength = 1.89 μm
- Laser: 1mm-long / 4 μm-wide



Short-wave infrared InP diode lasers

Laser performances

Central Wavelength	Max. Power
1450 nm	30 mW
1470 nm	50 mW
1550 nm	30 mW
1630 nm	50 mW
1650 nm	50 mW
1730 nm	30 mW
1740 nm	40 mW
1830 nm	50 mW
1890 nm	50 mW
2080 nm	20 mW
2100 nm	10 mW
2150 nm	50 mW

- 12 different wavelengths between 1.45 μm and 2.15 μm available
- Mature InP-based technology