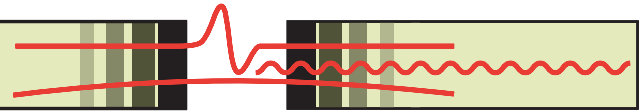


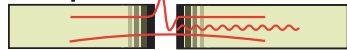
High power and single frequency quantum cascade lasers for chemical sensing

Stéphane Blaser



Collaborators

Alpes Lasers



Yargo Bonetti

Lubos Hvozدارa

Antoine Muller

Guillaume Vandeputte

Hege Andersen

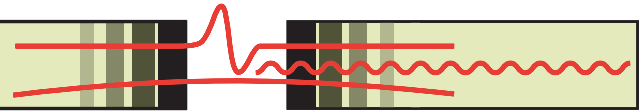


Marcella Giovannini

Nicolas Hoyler

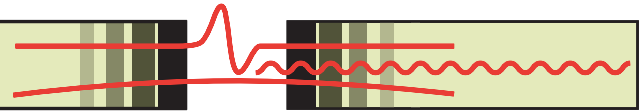
Mattias Beck

Jérôme Faist



Outline

- Company profile
 - Introduction - state of the art
 - High power Fabry-Pérot devices
 - Applications
 - Distributed-feedback lasers
 - High power pulsed DFB devices
 - >77K operating continuous-wave DFB devices
 - Reliability
 - Production
-

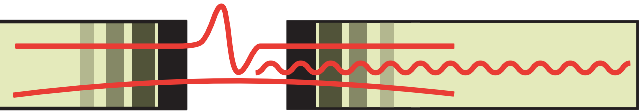


Company profile

- Founded August 1998 as a spin-off company from the University of Neuchâtel
 - incorporated as a SA under swiss law with a capital of 100 kCHF)
- Founders
 - Jérôme Faist
 - Antoine Muller
 - Mattias Beck
- Employees (September 2003)
 - 8 persons (6 full-time)



Installed at Maximilien-de-Meuron 1-3,
2000 Neuchâtel since April 2002

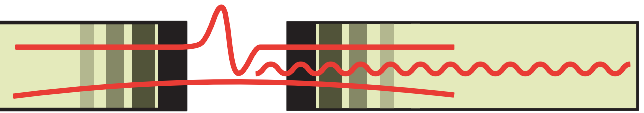


Company profile

- > 30 man-years experience
 - 7 patents on QCL technologies

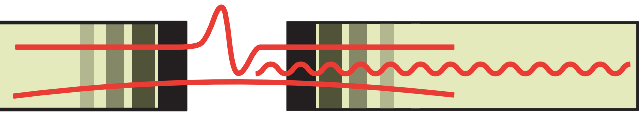
 - > 150 devices sold
 - > 50 customers

 - turnover 2003: > 1.3 MCHF
 - average growth rate: 100% / year
-

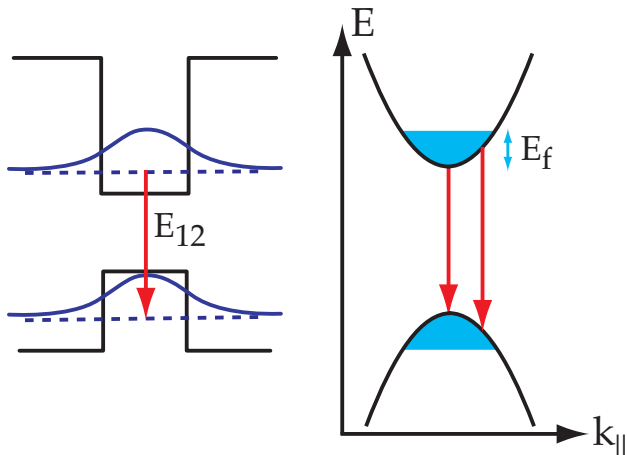


Quantum cascade lasers



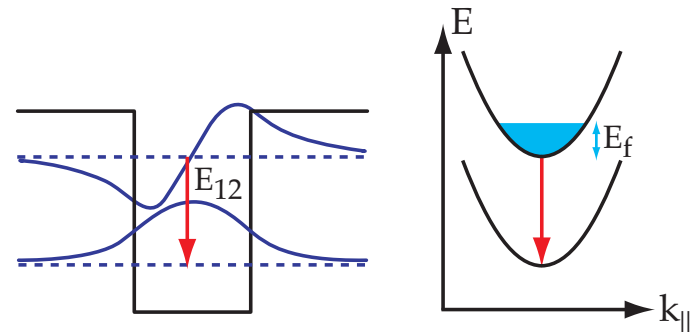


Interband vs intersubband



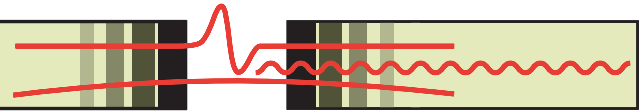
• Interband transition

- bipolar
- photon energy limited by bandgap E_g of material
- Telecom, CD, DVD, ...



• Intersubband transition

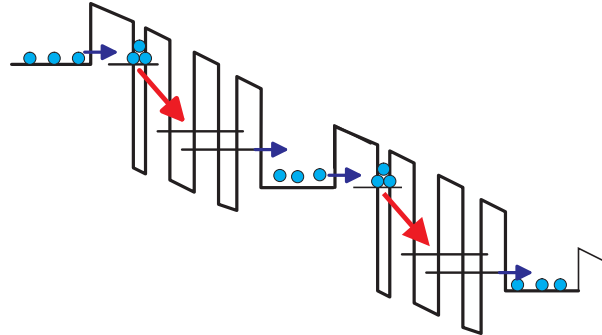
- unipolar, narrow gain
- photon energy depends on layer thickness and can be tailored



Quantum cascade lasers

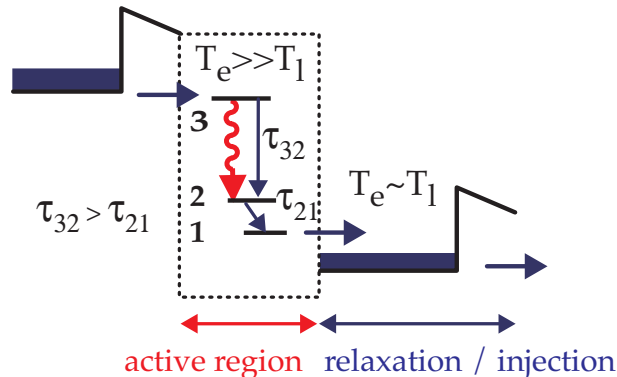
- **Cascade**

- each e- emits N photons



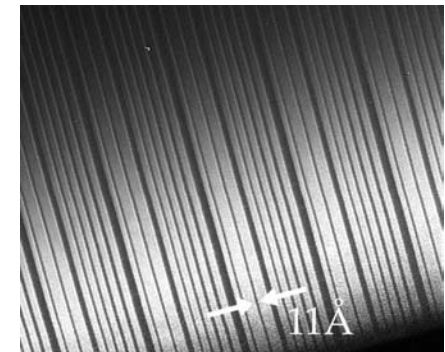
- **Active region / injector**

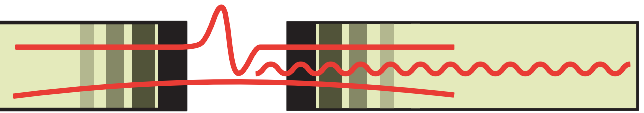
- active region → population inversion which must be engineered
- injector → avoid fields domains and cools down the electrons



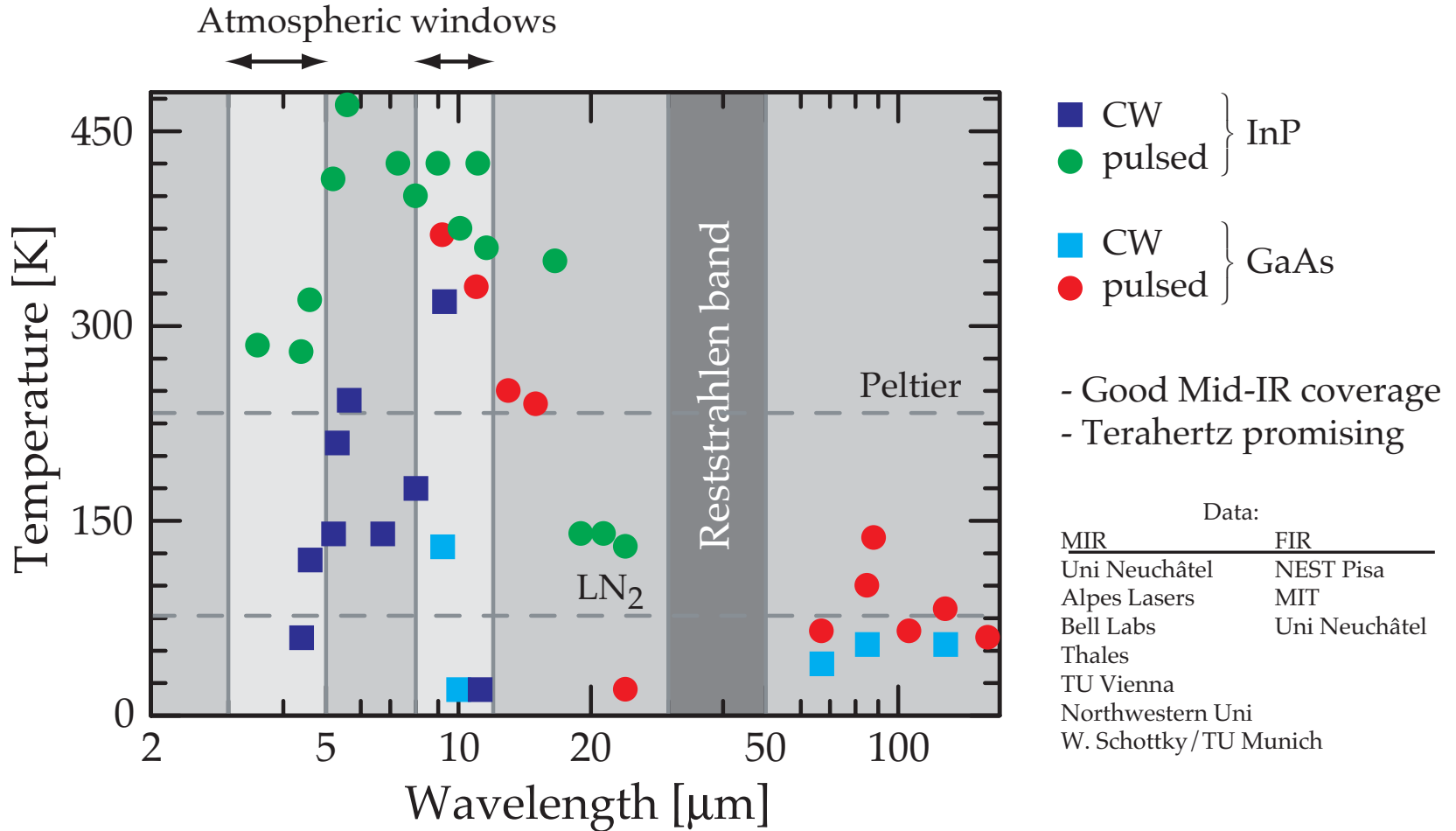
- **MBE**

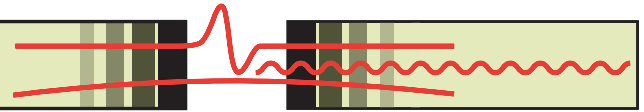
- growth of thin layers
- sharp interfaces





State of the art: QCL performances





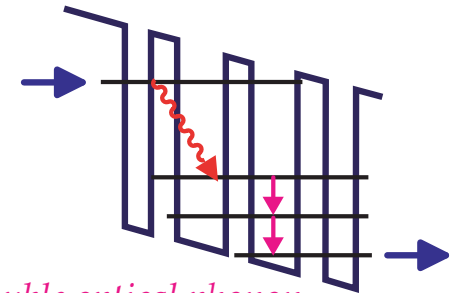
Designs

Double-phonon resonance:

(patent n° wo 02/23686A1)

- 4QW active region with 3 coupled lower state
- lower states separated by one phonon energy each
- keeps good injection efficiency of the 3QW design

Hofstetter *et al.* APL **78**, 396 (2001).



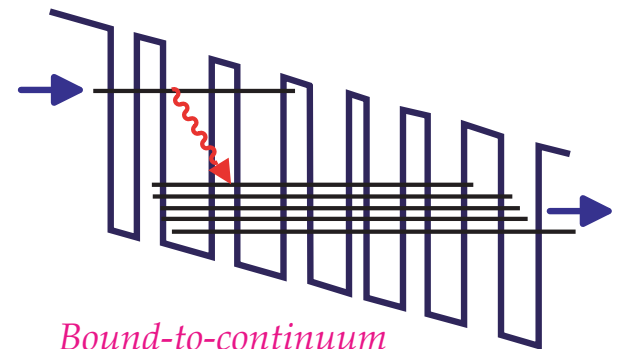
Double optical phonon resonance

Bound-to-continuum:

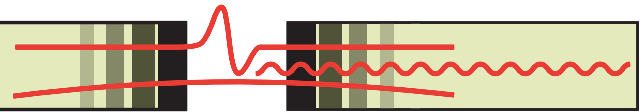
(patent n° wo 02/019485A1)

- transition from a bound state to a miniband
- combines injection and extraction efficiency
- broad gain curve -> good long-wavelength and high temperature operation

J. Faist *et al.* APL **78**, 147 (2001).



Bound-to-continuum



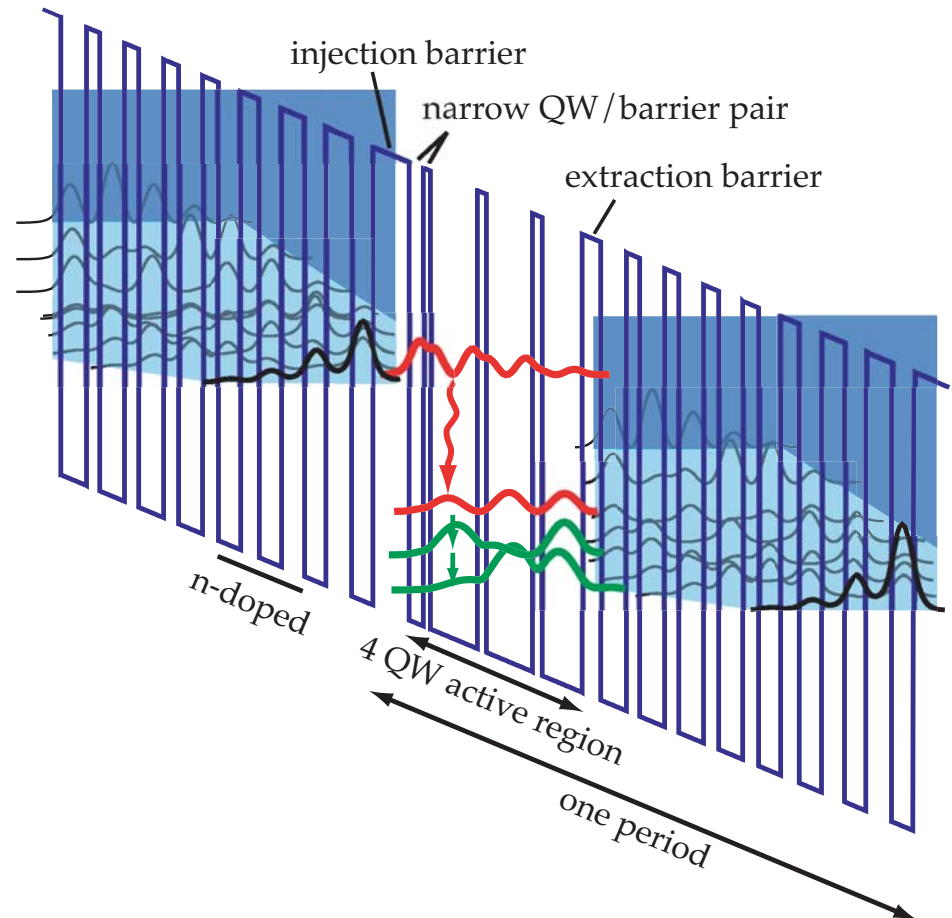
Two-phonon structure at 8 μm

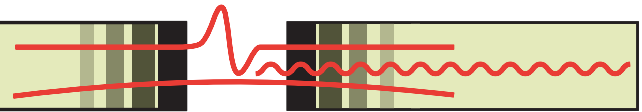
Based on two-phonon resonances design

InGaAs/InAlAs-based heterostructure with $\Delta E_c = 0.52\text{eV}$

Grown by MBE on InP substrate

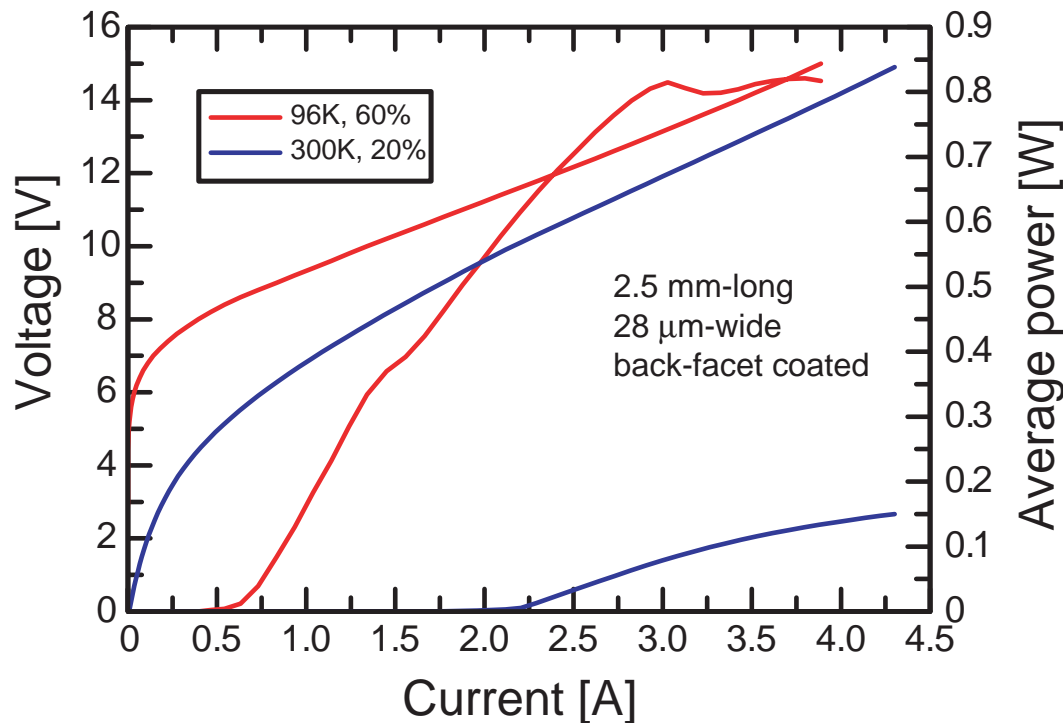
35 periods





High average power FP QCL

RT-HP-FP-150-1266



Characteristics

$\lambda = 7.9 \mu\text{m}$

@300K: Average power:

$P = 150 \text{ mW}$

threshold current:

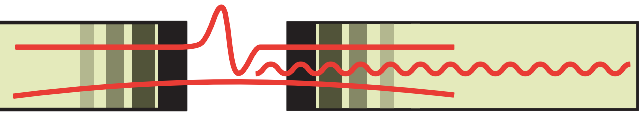
$I_{\text{th}} = 2.1 \text{ A}$ ($j_{\text{th}} = 3.0 \text{ kA/cm}^2$)

@96K : $P = 0.82 \text{ W}$ (60% dc)

$I_{\text{th}} = 0.51 \text{ A}$ ($j_{\text{th}} = 0.75 \text{ kA/cm}^2$)

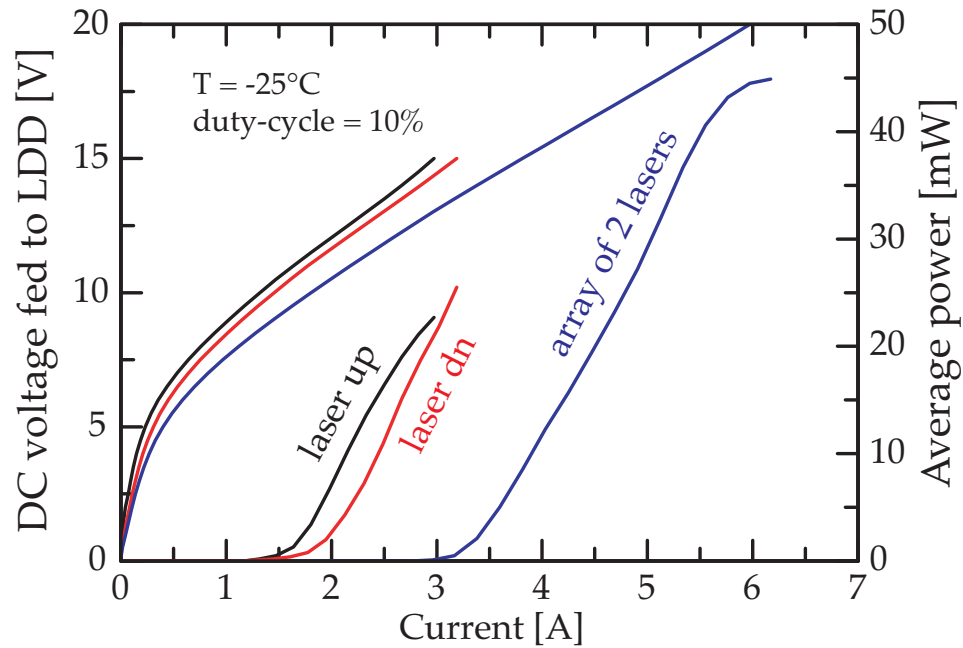
CW: $P = 300 \text{ mW}$

($j_{\text{th}} = 0.78 \text{ kA/cm}^2$)



Array of lasers

DUAL-RT-HP-FP-40-1266

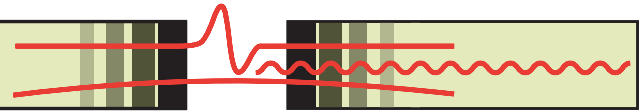


Characteristics

both lasers: 1.5 mm-long, $28\ \mu\text{m}$ -wide
 $\lambda \approx 7.9\ \mu\text{m}$
 $T = -25^\circ\text{C}$, duty-cyle = 10%

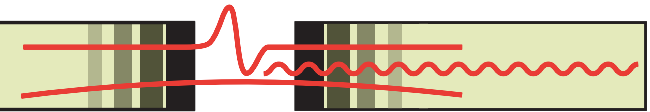
laser	Average power	I_{th} [A]	j_{th} [kA/cm^2]
up	25.4 mW	1.8	4.29
dn	22.6 mW	1.6	3.81
array	44.9 mW	3.4	4.05

- Total power $\approx 90\%$ ($P_1 + P_2$)
- Total threshold current $\approx I_1 + I_2$



Applications

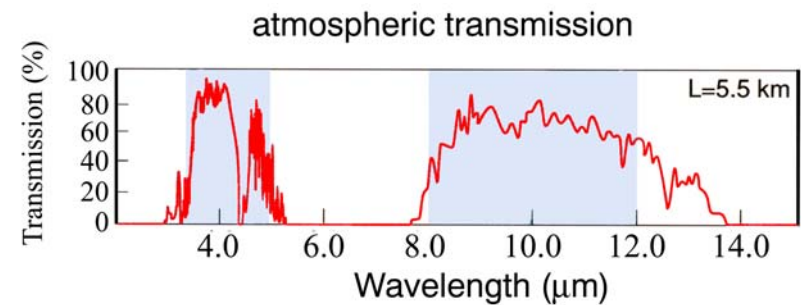
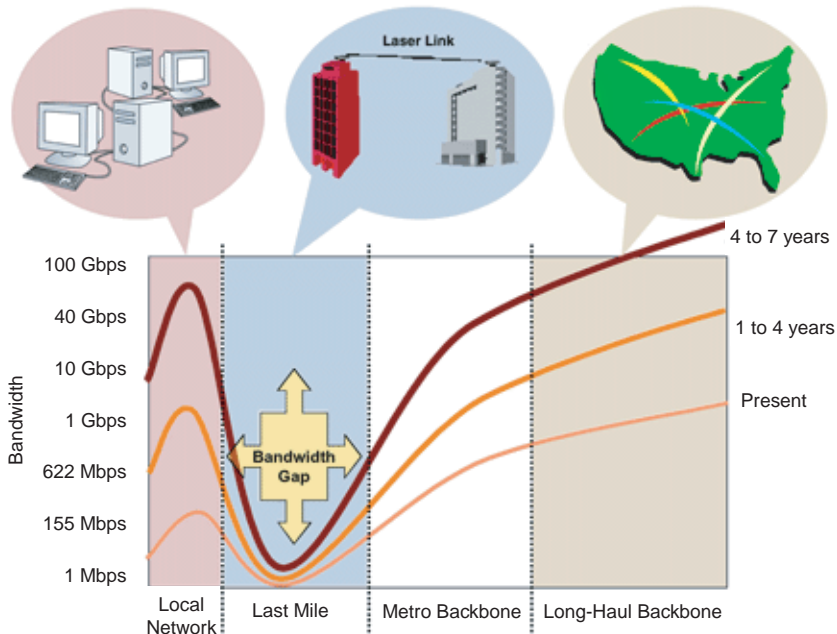




Applications: telecom

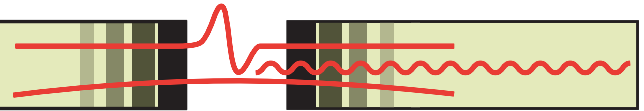
- Telecommunications

- Free-space optical data transmission for the last mile (high speed with no need for licence and better operation in fog, compared to $\lambda = 1.55 \mu\text{m}$)



R. Martini et al., IEE Elect. Lett. 37 (11), p. 1290, 2001.

S. Blaser et al., IEE Elect. Lett. 37 (12), p. 778, 2001.



Main application: chemical sensing by optical spectroscopy

Detection techniques already demonstrated using QCL:

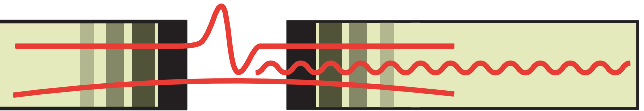
- photo-acoustic
 - B. Paldus et al., Opt. Lett. 24 (3), p.178, 1999.
 - D. Hofstetter et al., Opt. Lett. 26 (12), p. 887, 2001.
 - M. Nägele et al., Analytical Sciences 17 (4), p. 497, 2001.
- TILDAS
 - M. Zahniser et al. (Aerodyne Research), TDLS'03.
- cavity ringdown
 - B. Paldus et al., Opt. Lett. 25 (9), p. 666, 2000.
- absorption spectroscopy
 - A. Kosterev et al., Appl. Phys. B 75 (2-3), p. 351, 2002.
- heterodyne detection scheme
 - D. Weidmann et al., Opt. Lett. 29 (9), p. 704, 2003.
- cavity enhanced spectroscopy
 - D. Bear et al. (Los Gatos Research), TDLS'03.

Some needs:

high-power laser

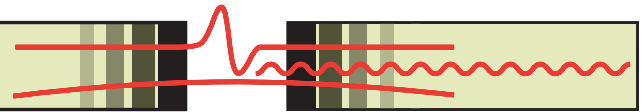
single mode

continuous-wave

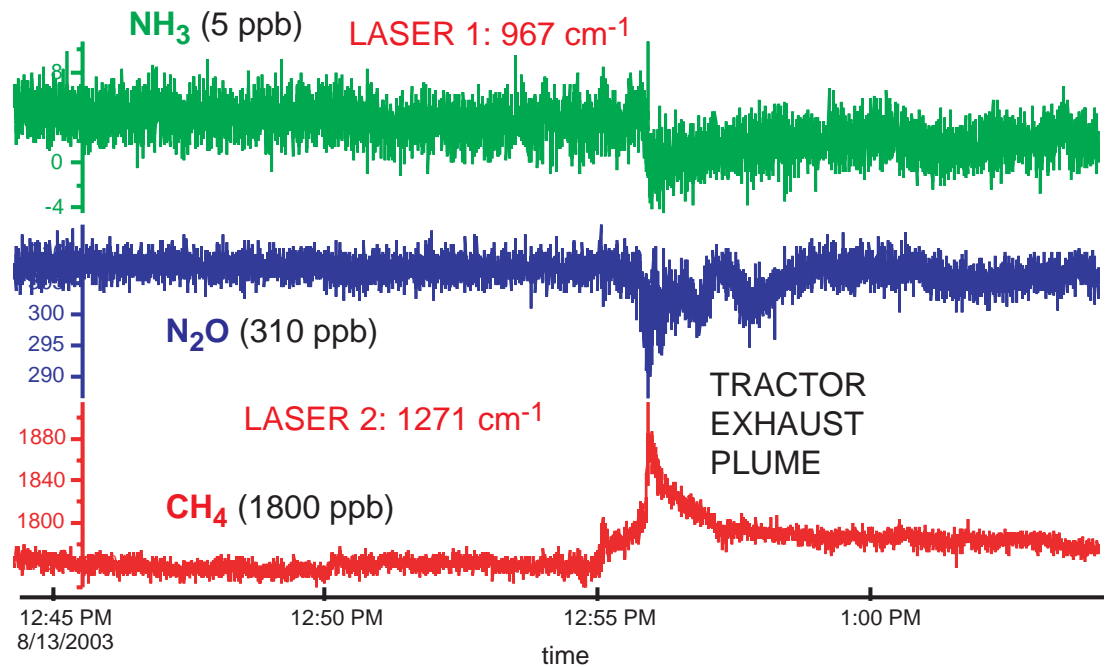
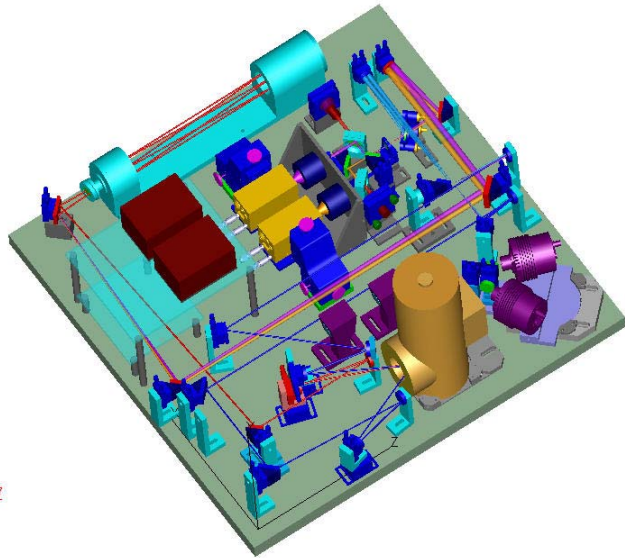


Application fields

- Chemical sensing or trace gas measurements
 - process development
 - environmental science
 - forensic science
 - process gas control
 - liquid detection spectroscopy
 - Medical diagnostics
 - breath analyzer
 - glucose dosage
 - Remote sensing
 - leak detection
 - exhaust plume measurement
 - combat gas detection
-



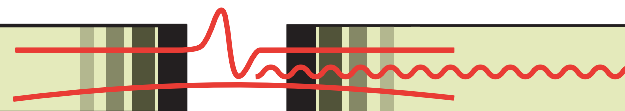
Simultaneous 3-gas measurements with dual-laser QCL instrument



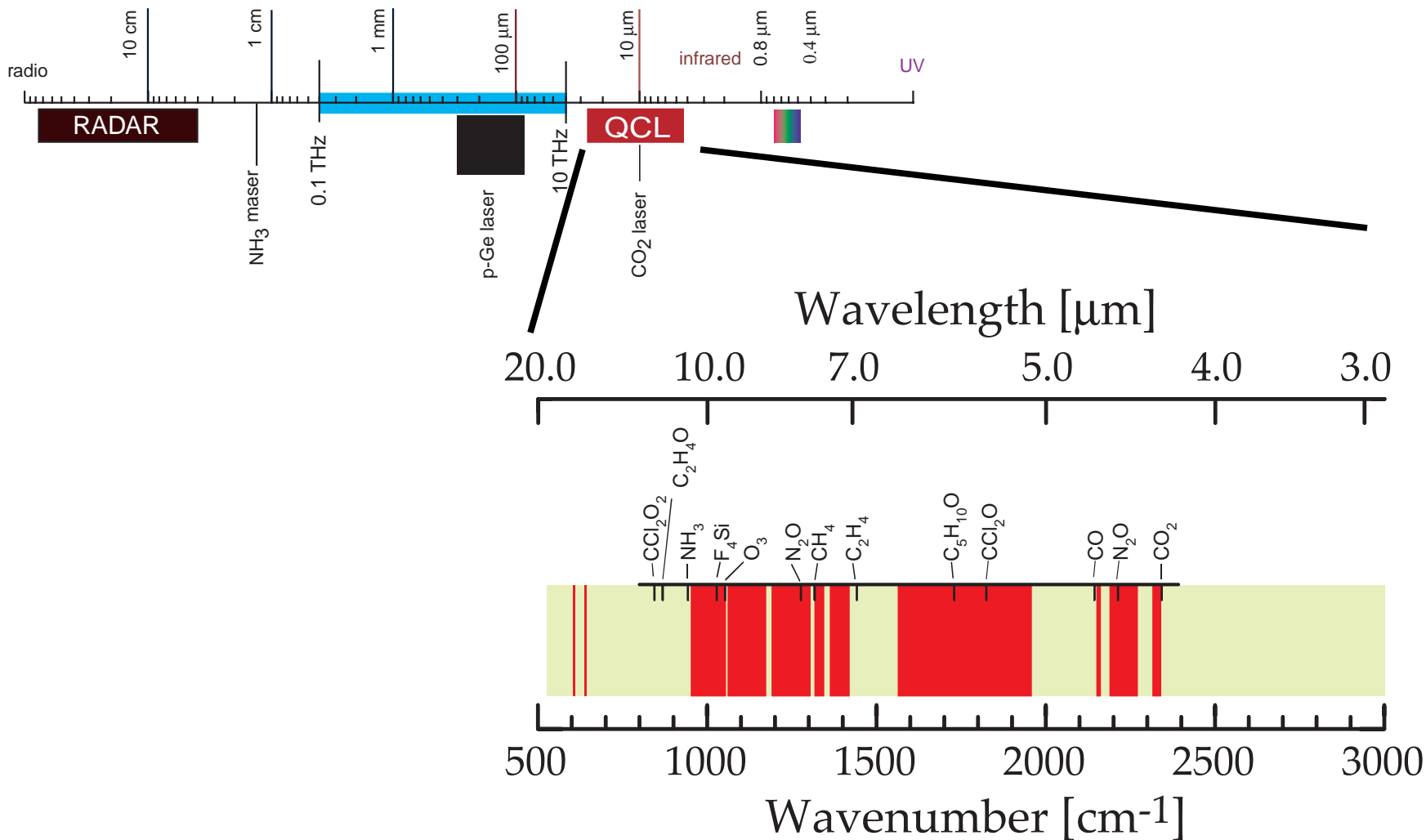
Two QC-lasers from Alpes:
 2 to 6 gases (CH₄, N₂O, NH₃)
 56 m cell path length
 Detector options

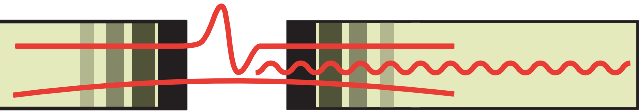


M. Zahniser et al.,
 Aerodyne Research Inc., Billerica (USA)



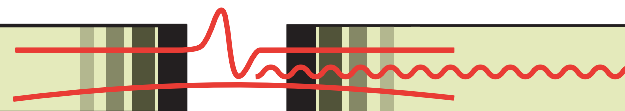
Spectrum covered by Alpes Lasers dfb QCLs





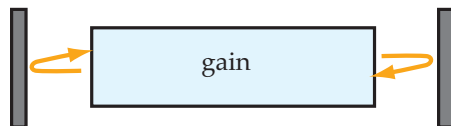
Single-mode operation: distributed-feedback QCLs





How does a DFB work?

Fabry-Pérot laser:



Amplified light bounces in the cavity

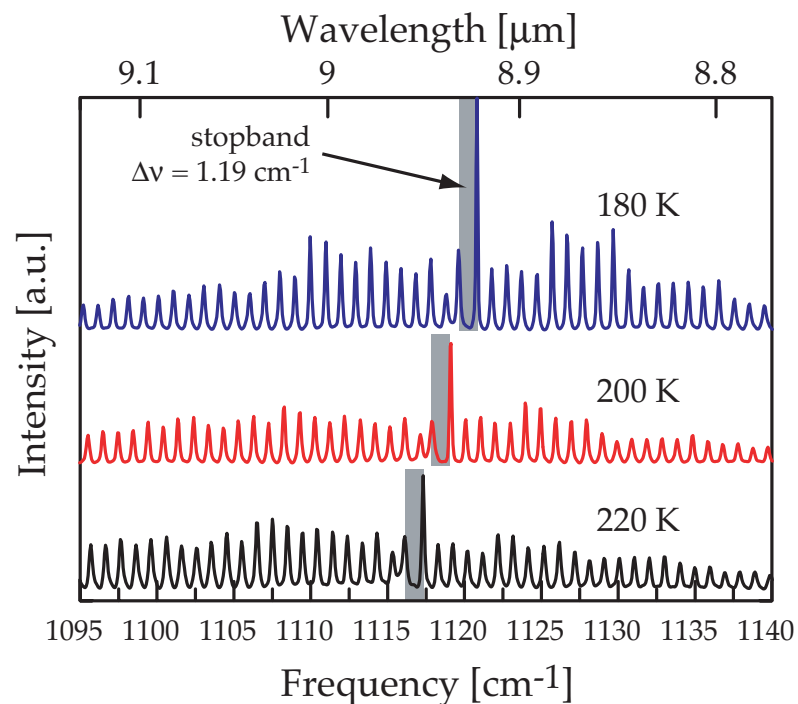
DFB:

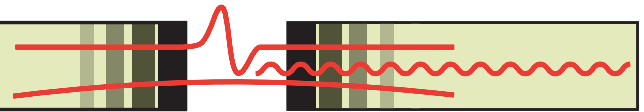
periodic grating => waves coupling
=> high wavelength selectivity



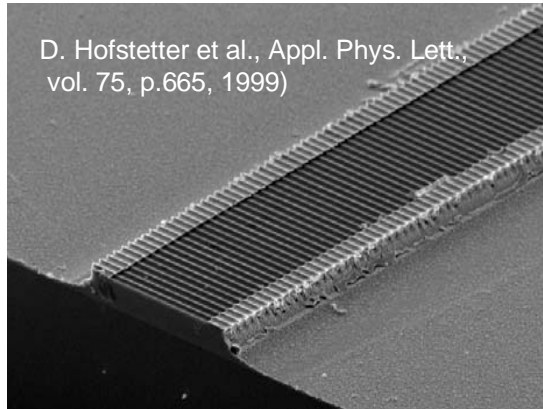
complex-coupled DFB:

- lasing mode closest to the stopband
- stopband \approx coupling strength



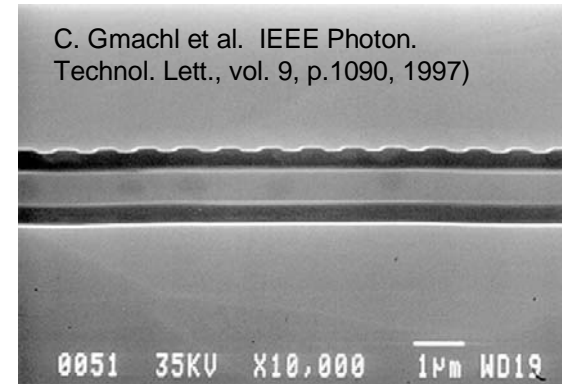


Distributed-feedback technologies



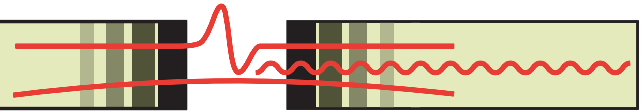
Grating on the surface (open-top)

- one MBE run (no MOCVD)
- high peak power (large stripes) but low average power
- optical losses due to metalization



Grating close to active region

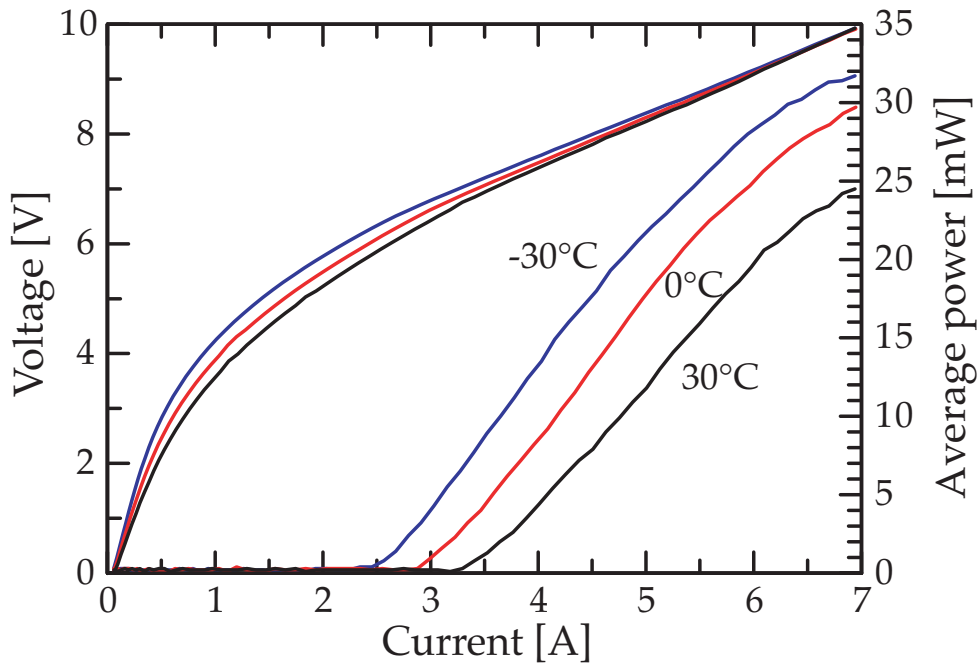
- lower thermal resistance (high duty / high temperature)
- high average power
- higher overlap, smaller losses
- jct dn mounting possible
- needs MOCVD regrowth



High average power DFB QCL

RT-HP-DFB-20-1200

Distributed feedback QC laser at $8.35\mu\text{m}$ with InP top cladding



Characteristics

3mm-long, $28\mu\text{m}$ -wide laser
 $\lambda \approx 8.35 \mu\text{m}$

@-30°C: Average power (2% dc):

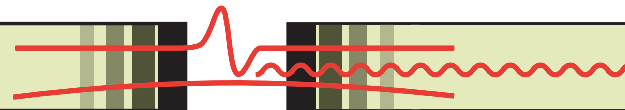
$P = 32 \text{ mW}$ (1.6 W peak power)

threshold current:

$I_{\text{th}} = 2.44 \text{ A}$ ($j_{\text{th}} = 2.9 \text{ kA/cm}^2$)

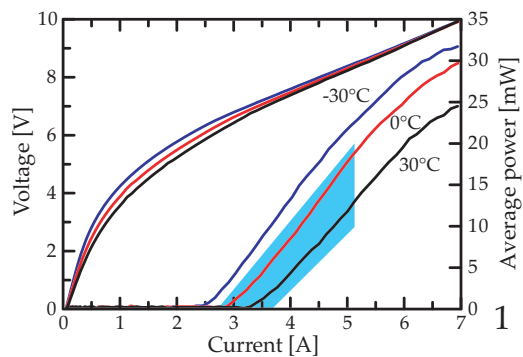
@30°C : $P = 25 \text{ mW}$ (1.25W peak power)

$I_{\text{th}} = 3.2 \text{ A}$ ($j_{\text{th}} = 3.8 \text{ kA/cm}^2$)



High average power DFB QCL

RT-HP-DFB-20-1200

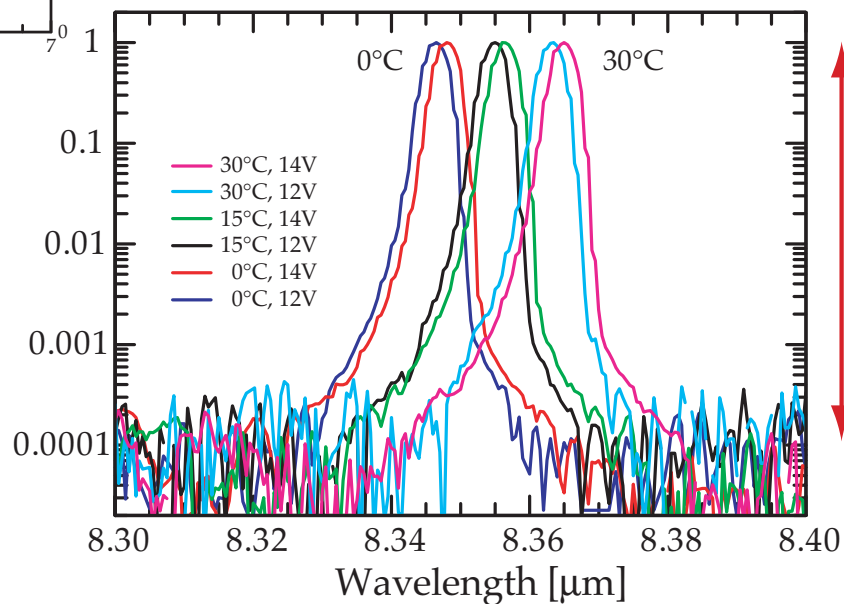


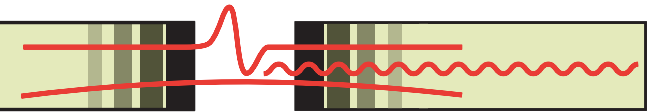
Characteristics

Entire tuning range:

$$\Delta\nu = 5.7 \text{ cm}^{-1} \text{ at } 1197 \text{ cm}^{-1} \text{ (0.47\%)}$$

$$(1195.2 \text{ cm}^{-1} \text{ (8.367 } \mu\text{m)}) \text{ at } 30^\circ\text{C} \text{ to } 1200.9 \text{ cm}^{-1} \text{ (8.327 } \mu\text{m)} \text{ at } -30^\circ\text{C}$$



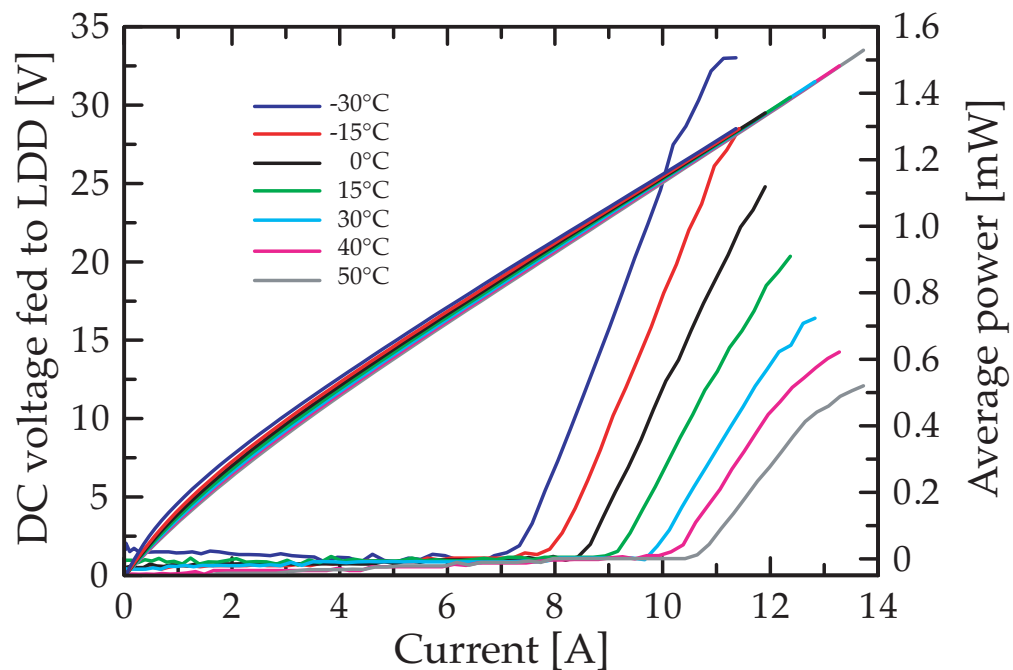


Long-wavelength ($\lambda \approx 16.4 \mu\text{m}$) B2C DFB QCL

RT-P-DFB-1-608

Laser based on a bound to continuum design, $\lambda \approx 16.4 \mu\text{m}$

Rochat et al., APL **79**, 4271 (2001)

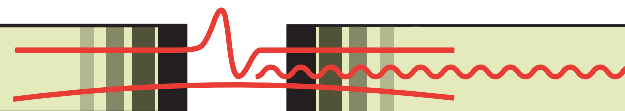


Characteristics

3 mm-long, 44 μm -wide laser
 $\lambda \approx 16.4 \mu\text{m}$

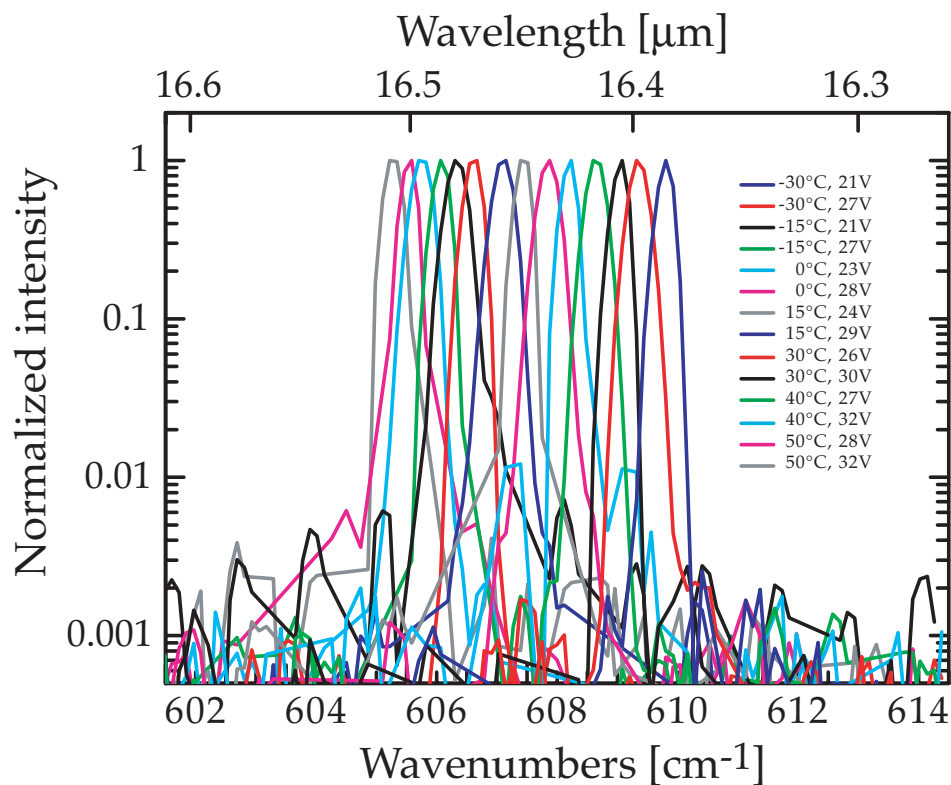
@-30°C: Average power (1.5% dc):
 $P = 1.5 \text{ mW}$ (100 mW peak power)
 Threshold current:
 $I_{\text{th}} = 7.1 \text{ A}$ ($j_{\text{th}} = 5.4 \text{ kA/cm}^2$)

@50°C : $P = 0.5 \text{ mW}$ (33 mW peak power)
 $I_{\text{th}} = 10.4 \text{ A}$ ($j_{\text{th}} = 7.9 \text{ kA/cm}^2$)



Long-wavelength ($\lambda \approx 16.4 \mu\text{m}$) B2C DFB QCL

RT-P-DFB-1-608



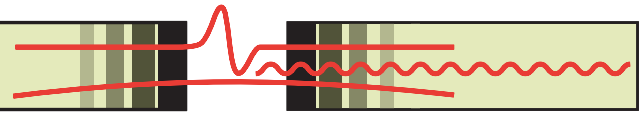
Characteristics

3mm-long, 44μm-wide laser
 $\lambda \approx 16.4 \mu\text{m}$

Single-mode emission:
 Side Mode Suppression Ratio > 25 dB
 (limited by the resolution of the FTIR)

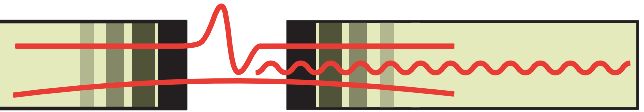
Tuning range:
 $\Delta\nu = 4.5 \text{ cm}^{-1}$ at 608 cm^{-1} (0.7%)

(605.76 cm^{-1} (16.51 μm) at 50°C to
 610.30 cm^{-1} (16.38 μm) at -30°C)



How does a DFB tune?

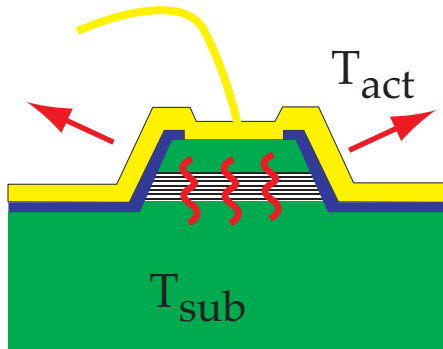




How does a DFB tune?

Tuning always due to thermal drift

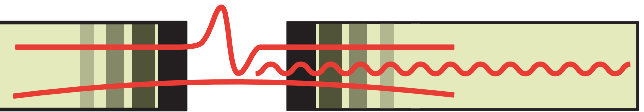
(carrier effects can be neglected!)



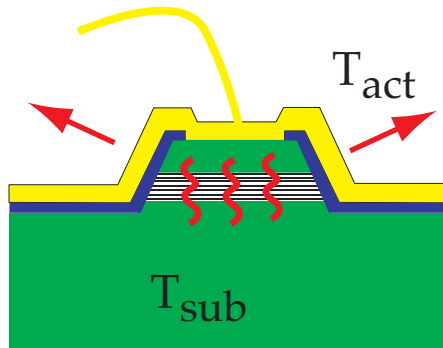
wavelength selection: $\lambda = 2 \cdot n_{eff} \cdot \Lambda_{grating}$

$$n_{eff} = n_{eff}(T)$$

$$\frac{d\lambda}{\lambda} = \frac{dn_{eff}}{n_{eff}}$$



How does a DFB tune?



Active region heating:

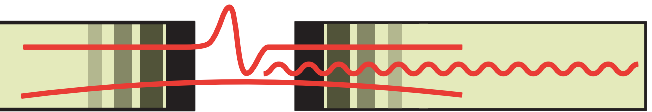
$$T_{\text{act}} = T_{\text{sub}} + I \cdot U \cdot \delta \cdot R_{\text{th}} (+ I_{\text{DC}} U_{\text{DC}} \cdot R_{\text{th}})$$

$$\Delta T = T_{\text{act}} - T_{\text{sub}}$$

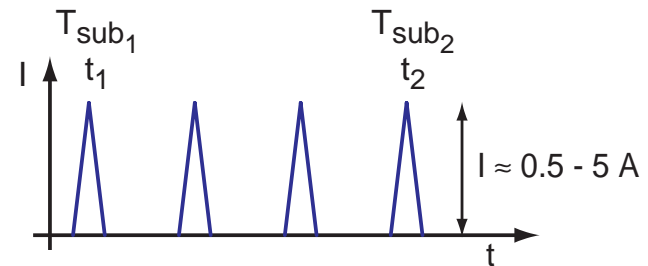
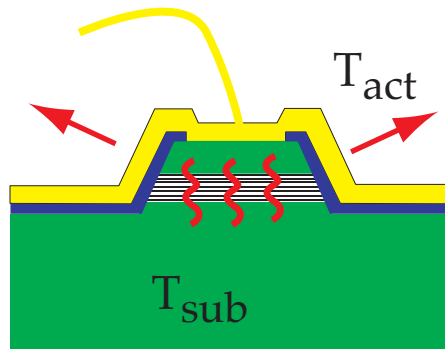
- If $\Delta T = 100^\circ\text{C}$ \Rightarrow 100% chance of laser-destruction (thermal stress)
 $= 60^\circ\text{C}$ \Rightarrow depends of mounting / laser -> dangerous
 $= 30^\circ\text{C}$ \Rightarrow OK

Different possibilities of thermal tuning: {

- substrate temperature
- additional bias current
- pulse length (chirping)
- pulse current
- duty-cycle

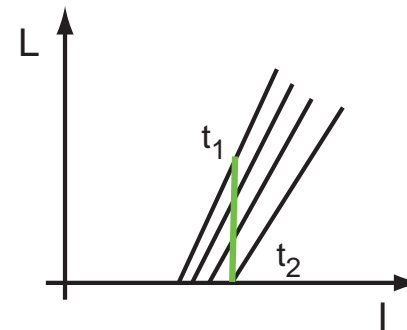


Tuning by changing T_{sub} (heatsink temperature)

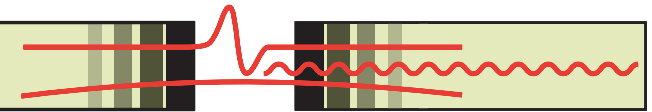


tuning coefficient:

$$\frac{1}{\lambda} \frac{\Delta\lambda}{\Delta T_{\text{sub}}} = \frac{1}{n_{\text{eff}}} \frac{\Delta n_{\text{eff}}}{\Delta T_{\text{sub}}} \approx [6 - 7] \cdot 10^{-5} \text{ K}^{-1}$$

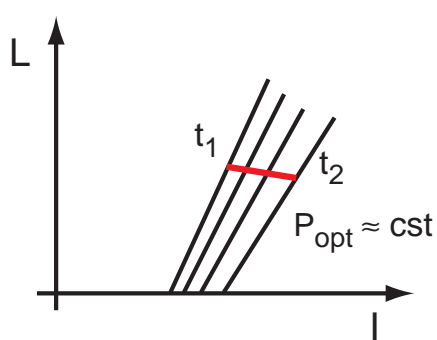
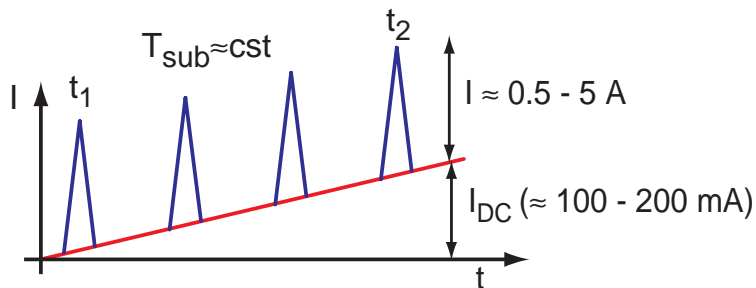


$\Delta T \approx 60^\circ\text{C} \Rightarrow -0.4\% \Delta\nu/\nu @ 0.01\text{Hz}$



Tuning by DC bias-induced heating

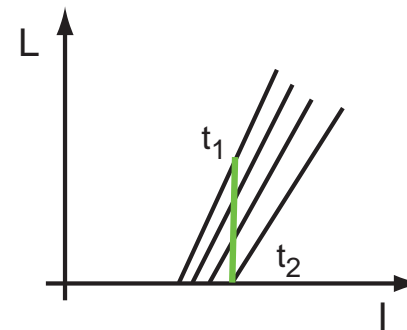
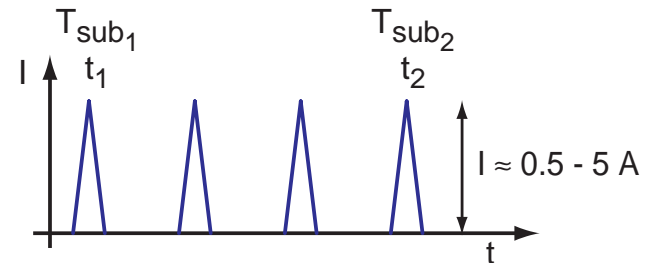
by DC bias-induced heating



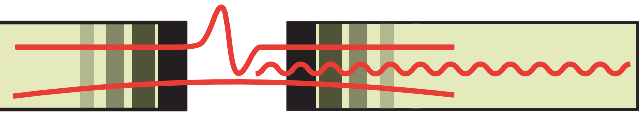
$$R_{th} = \frac{\Delta T}{V_{device} \cdot I_{DC}}$$

$\Delta T \approx 30^\circ\text{C} \Rightarrow -0.2\% \Delta v/v @ >1\text{kHz}$

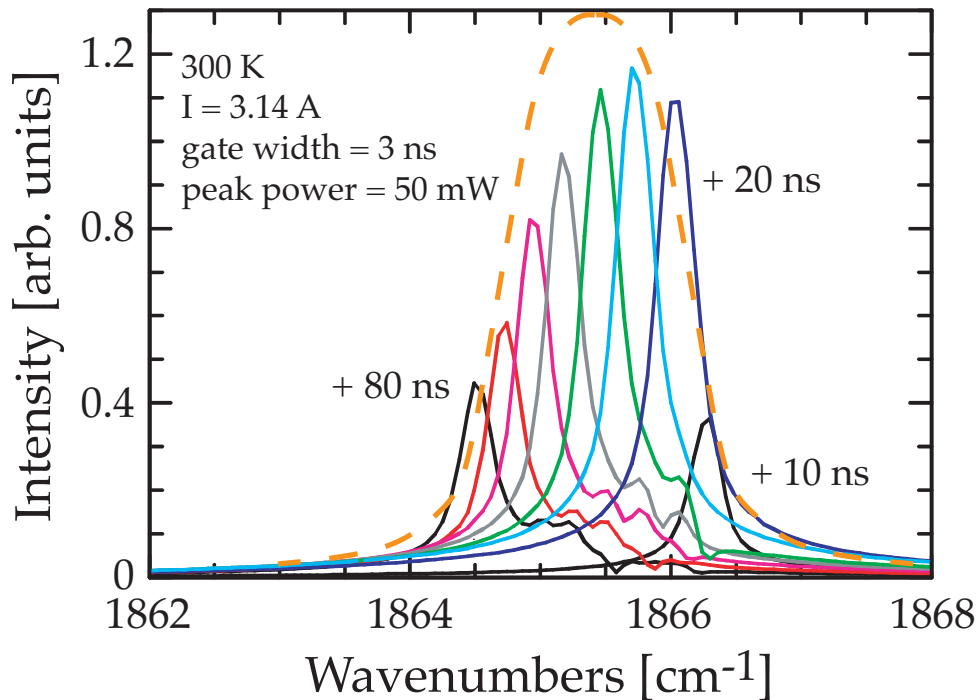
by changing T_{sub}



$\Delta T \approx 60^\circ\text{C} \Rightarrow -0.4\% \Delta v/v @ 0.01\text{Hz}$

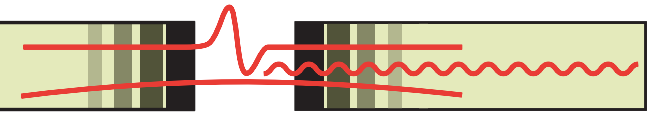


Thermal chirping during pulse

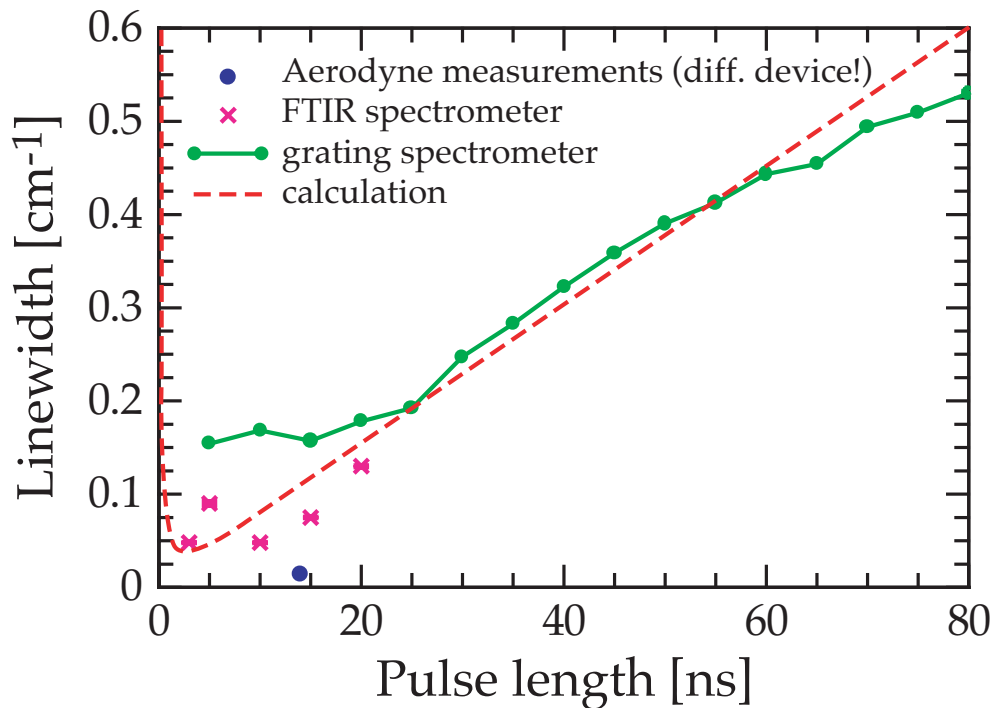


drift with time: $0.03 \text{ cm}^{-1}/\text{ns}$
(high dissipated power)

20 K temperature increase of
during a 100-ns-long pulse



Pulse length dependence of linewidth

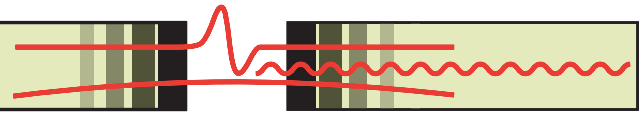


Need for a good compromise:

- too long: limited by thermal chirping
- too short: limited by the time evolution of the lasing mode

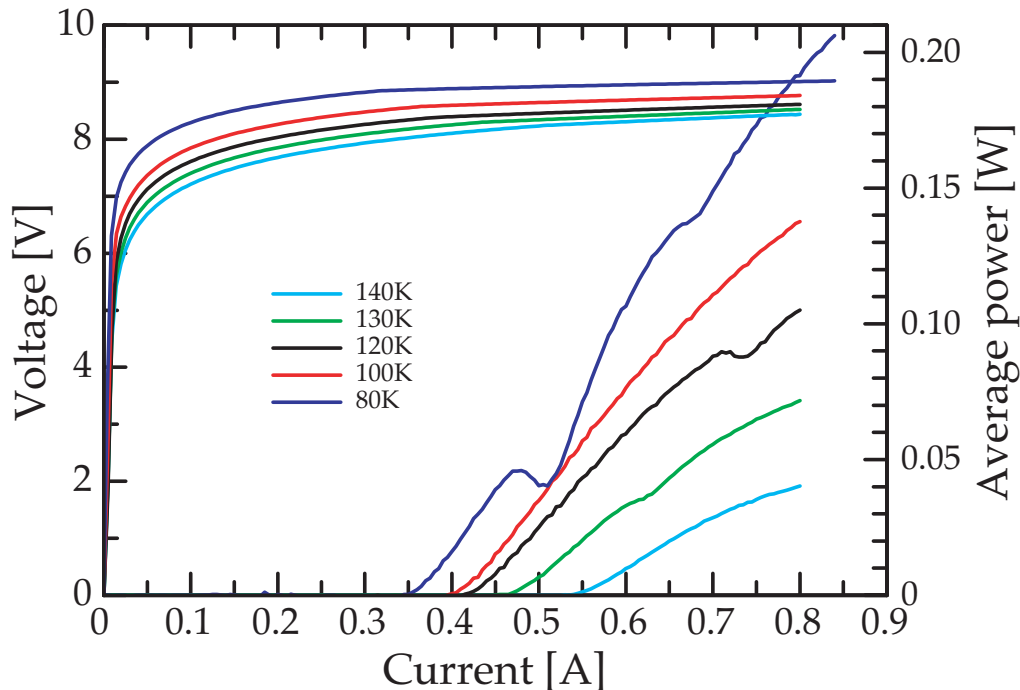
→ fundamental limits

→ for narrower linewidth:
cw operation



CW operation at $\lambda \approx 6.73\mu\text{m}$

LN2-CW-DFB-100-1485

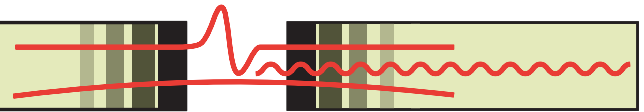


Characteristics

1.5 mm-long, 23 μm -wide laser
CW operation at $\lambda \approx 6.73\ \mu\text{m}$

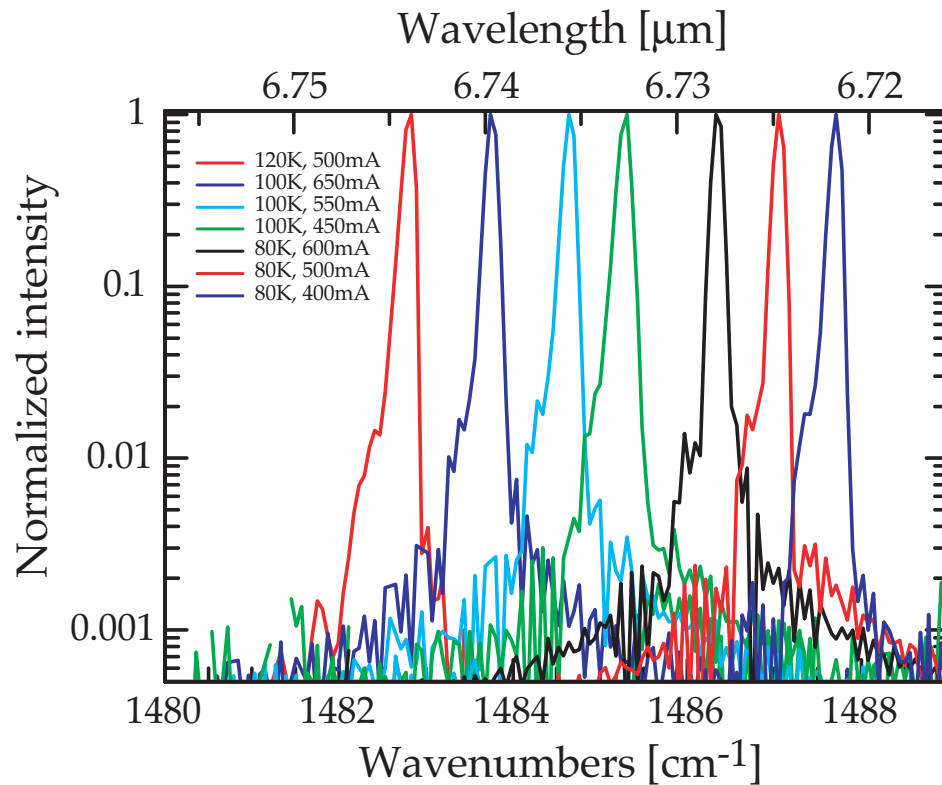
@80 K: Average power $P = 0.2\ \text{W}$
Threshold current:
 $I_{\text{th}} = 0.35\ \text{A}$ ($j_{\text{th}} = 1.0\ \text{kA/cm}^2$)

$I_{\text{op}} < 0.8\ \text{A}$
 $U_{\text{op}} < 9\ \text{V}$



CW operation at $\lambda \approx 6.73\mu\text{m}$

LN2-CW-DFB-100-1485



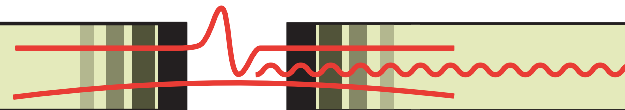
Characteristics

1.5 mm-long, 23 μm -wide laser
 CW operation at $\lambda \approx 6.73\mu\text{m}$

Single-mode emission:
 Side Mode Suppression Ratio > 30 dB
 (limited by the resolution of the FTIR)

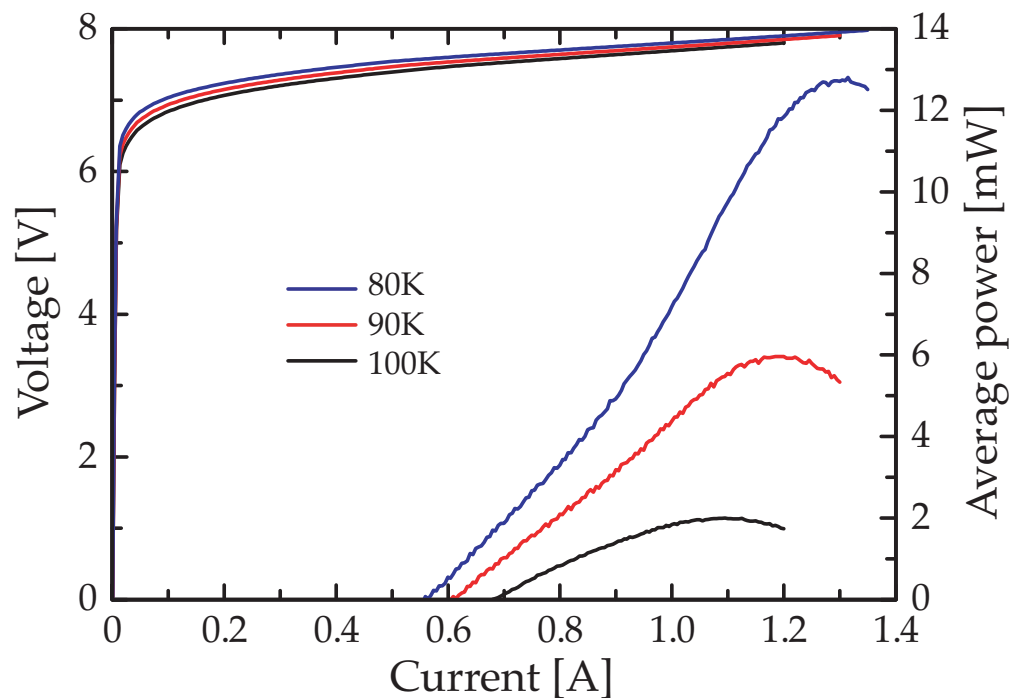
Tuning range:
 $\Delta\nu = 4.9\text{ cm}^{-1}$ at 1485 cm^{-1} (0.33%)

(1482.8 cm^{-1} ($6.744\mu\text{m}$) at 120K to
 1487.7 cm^{-1} ($6.722\mu\text{m}$) at 80K)



CW operation at $\lambda \approx 4.60\mu\text{m}$

LN2-CW-DFB-10-2171

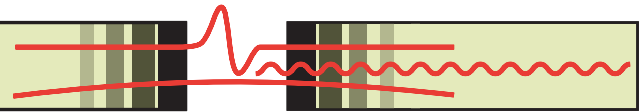


Characteristics

1.5 mm-long, 21 μm -wide laser
CW operation at $\lambda \approx 4.60\mu\text{m}$

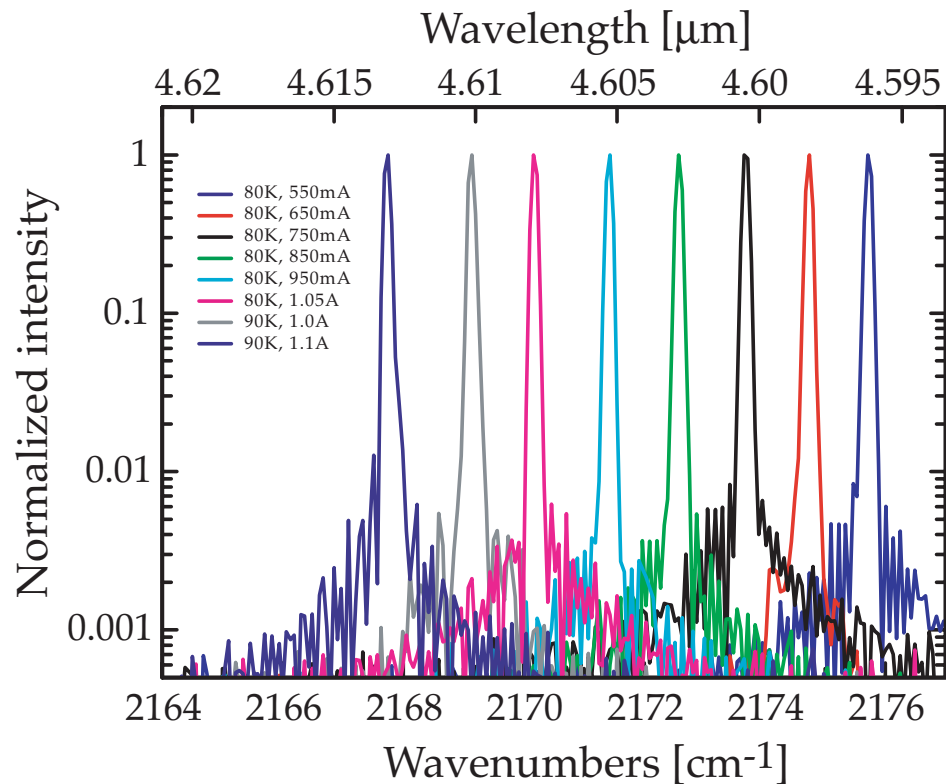
@80 K: Average power $P = 12\text{ mW}$
Threshold current density:
 $I_{\text{th}} = 0.54\text{ A}$ ($j_{\text{th}} = 1.7\text{ kA/cm}^2$)

$I_{\text{op}} < 1.1\text{ A}$
 $U_{\text{op}} < 8\text{ V}$



CW operation at $\lambda \approx 4.60\mu\text{m}$

LN2-CW-DFB-10-2171



Characteristics

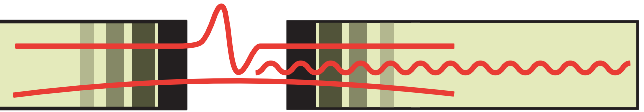
1.5 mm-long, 21 μm -wide laser
 CW operation at $\lambda \approx 4.60\mu\text{m}$

Single-mode emission:
 Side Mode Suppression Ratio > 25 dB
 (limited by the resolution of the FTIR)

Tuning range:

$\Delta\nu = 8\text{ cm}^{-1}$ at 2171 cm^{-1} (0.37%)

(2167.7 cm^{-1} ($4.613\mu\text{m}$) at 90K to
 2175.7 cm^{-1} ($4.596\mu\text{m}$) at 80K)

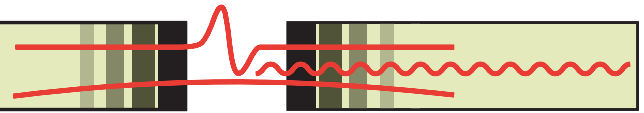


Future:

**continuous-wave and single-mode
operation at room-temperature**

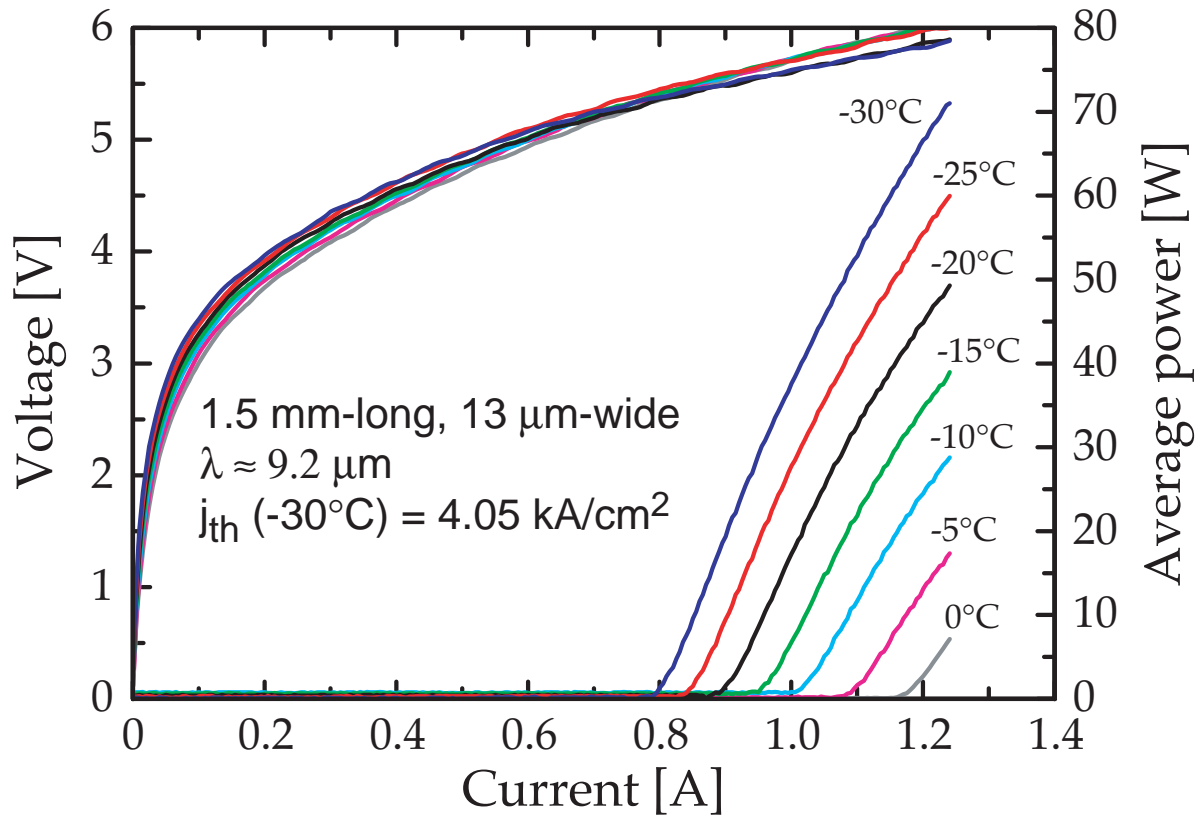
terahertz sources



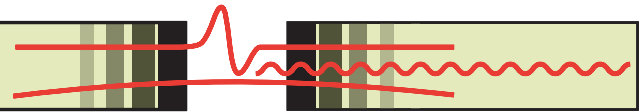


Continuous-wave FP QCL on Peltier

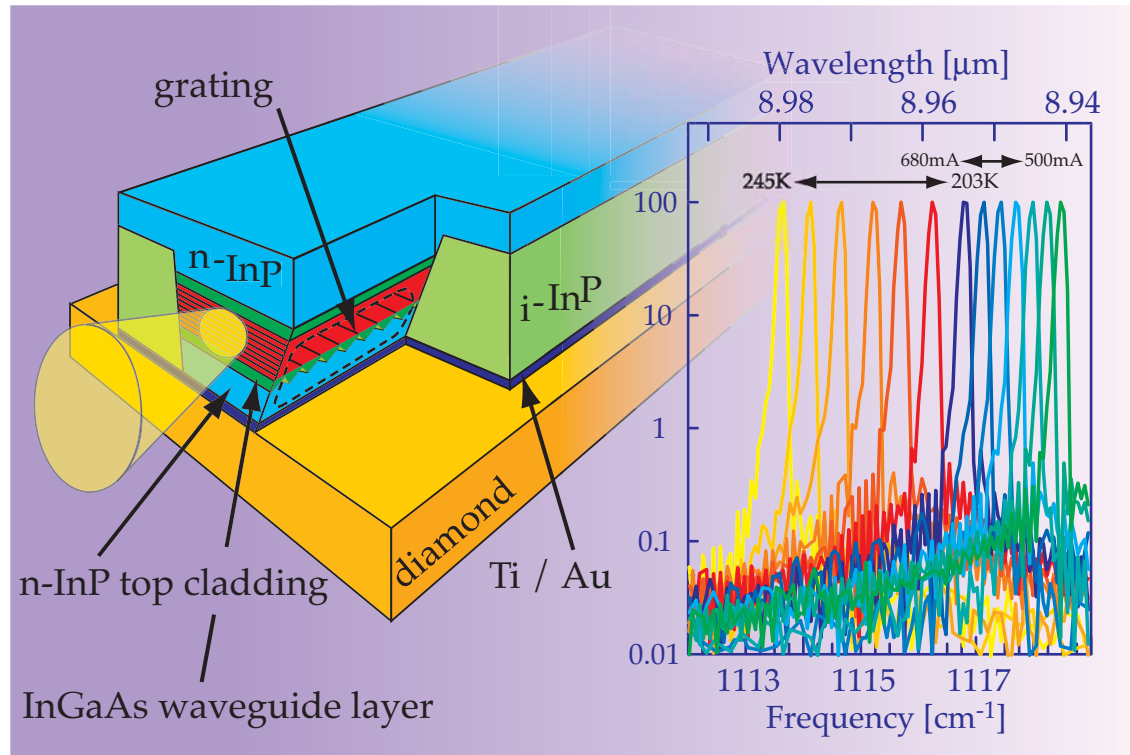
RT-CW-FP-50-1080



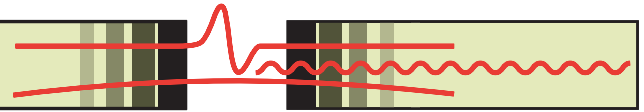
$I_{\text{op}} < 1.2 \text{ A}$
 $U_{\text{op}} < 6 \text{ V}$



BH distributed-feedback QCLs



Continuous-wave distributed-feedback quantum-cascade lasers on a Peltier cooler. T. Aellen, S. Blaser, M. Beck, D. Hofstetter, J. Faist, and E. Gini, *Appl. Phys. Lett.* **83**, p.1929, 2003.



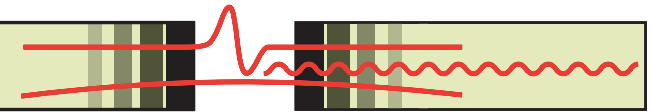
THz applications

New sources: R. Köhler et al., Nature 417, p.156, 2002.

M. Rochat et al., Appl. Phys. Lett. 81 (8), p.1381, 2002.

Terahertz applications:

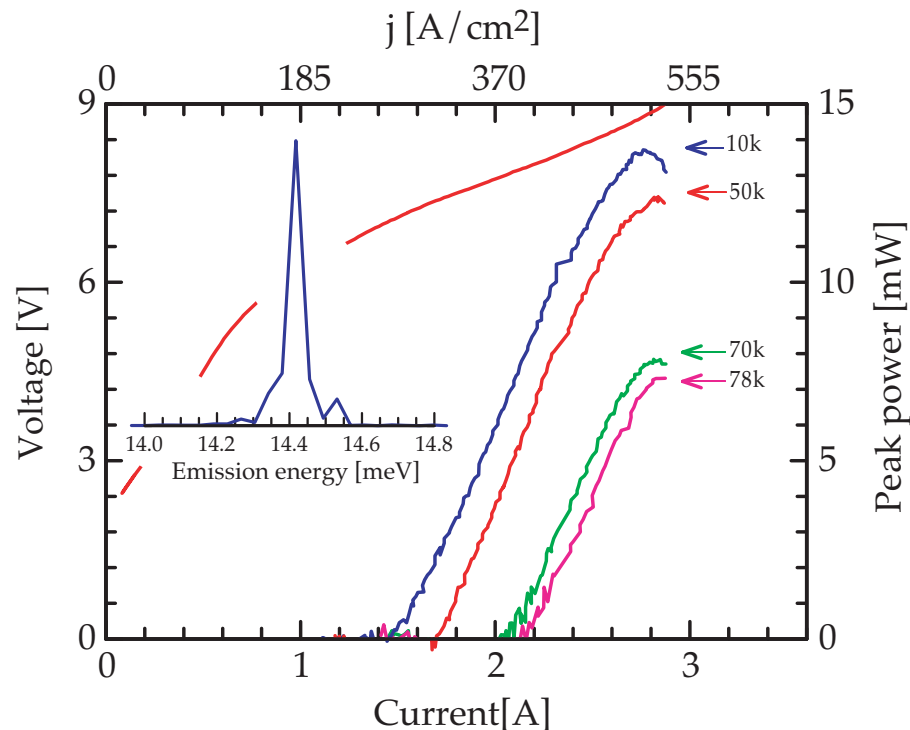
- Astronomy
 - Medical imaging
 - Chemical detection
 - Telecommunications for local area network (LAN)
-



Terahertz sources

THz QC laser based on a bound to continuum design, $\lambda \approx 87 \mu\text{m}$

Structure grown at University of Neuchâtel (G. Scalari, L. Ajili, M. Beck and M. Giovannini)

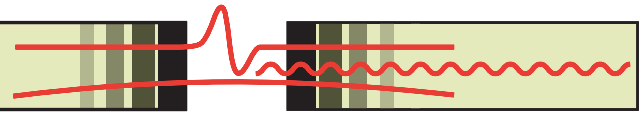


Characteristics

THz QC laser: $\lambda \approx 87 \mu\text{m}$
 2.7mm-long, 200 μm -wide laser
 back-facet coated

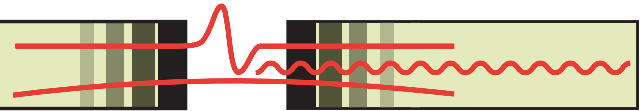
@10 K: Peak power (2.5% dc):
 $P = 14 \text{ mW}$
 threshold current density:
 $j_{\text{th}} = 267 \text{ A/cm}^2$

pulsed operation up to 78K
 CW operation up to 30 K

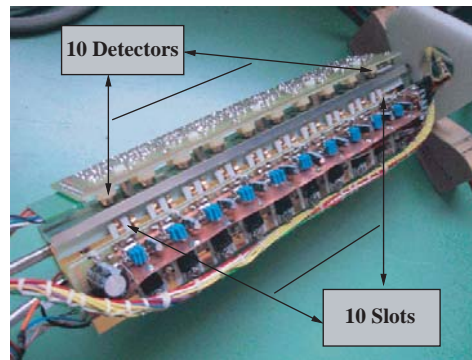
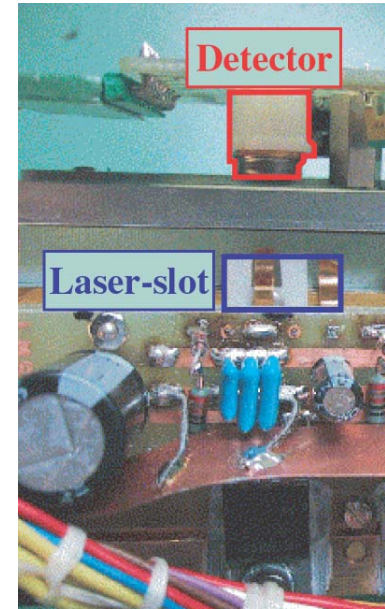
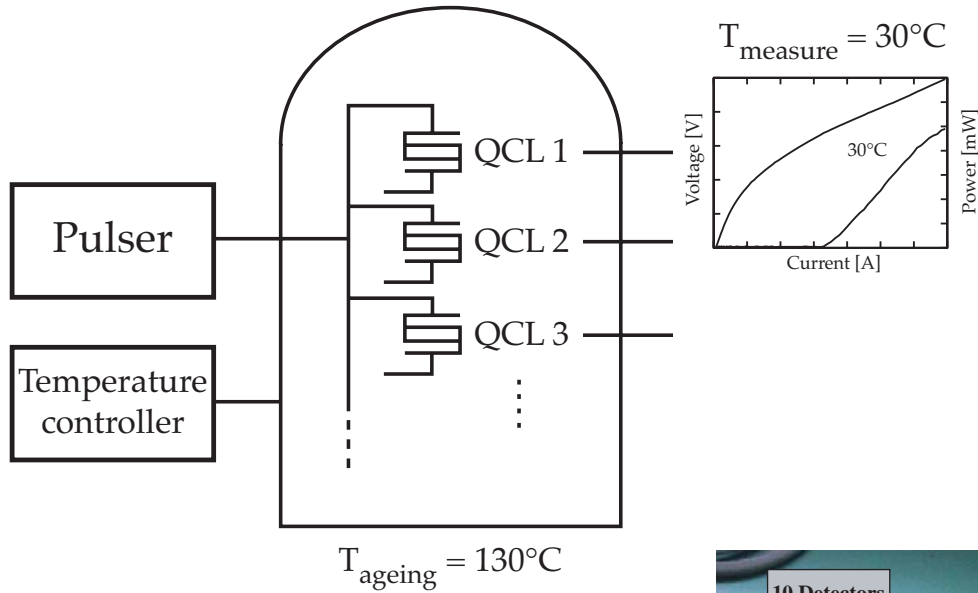


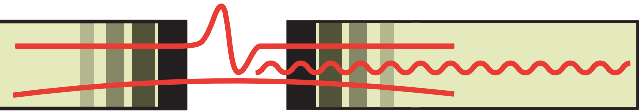
Reliability of the devices





Reliability of the devices: ageing





Ageing: theory

Conversion of lifetime using Arrhenius type relation: $t \sim \exp[E/(kT)]$

where: t is lifetime

T temperature

$E=0.7$ eV activation energy [H. Ishikawa et al., J. Appl. Phys. **50**, 1979]

(needs to be evaluated for QCL)

The room temperature lifetime t_1 (at $T_1 = 20^\circ\text{C}$ and 70% of initial power) can be extrapolated by :

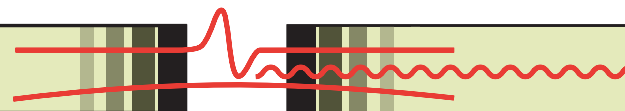
$$t_1 = t_0 \cdot e^{\frac{E}{k} \cdot \frac{1}{T_1} - \frac{1}{T_0}}$$

with t_0 is the measured lifetime at the ageing temperature T_0 (here $130^\circ\text{C} = 403\text{K}$).

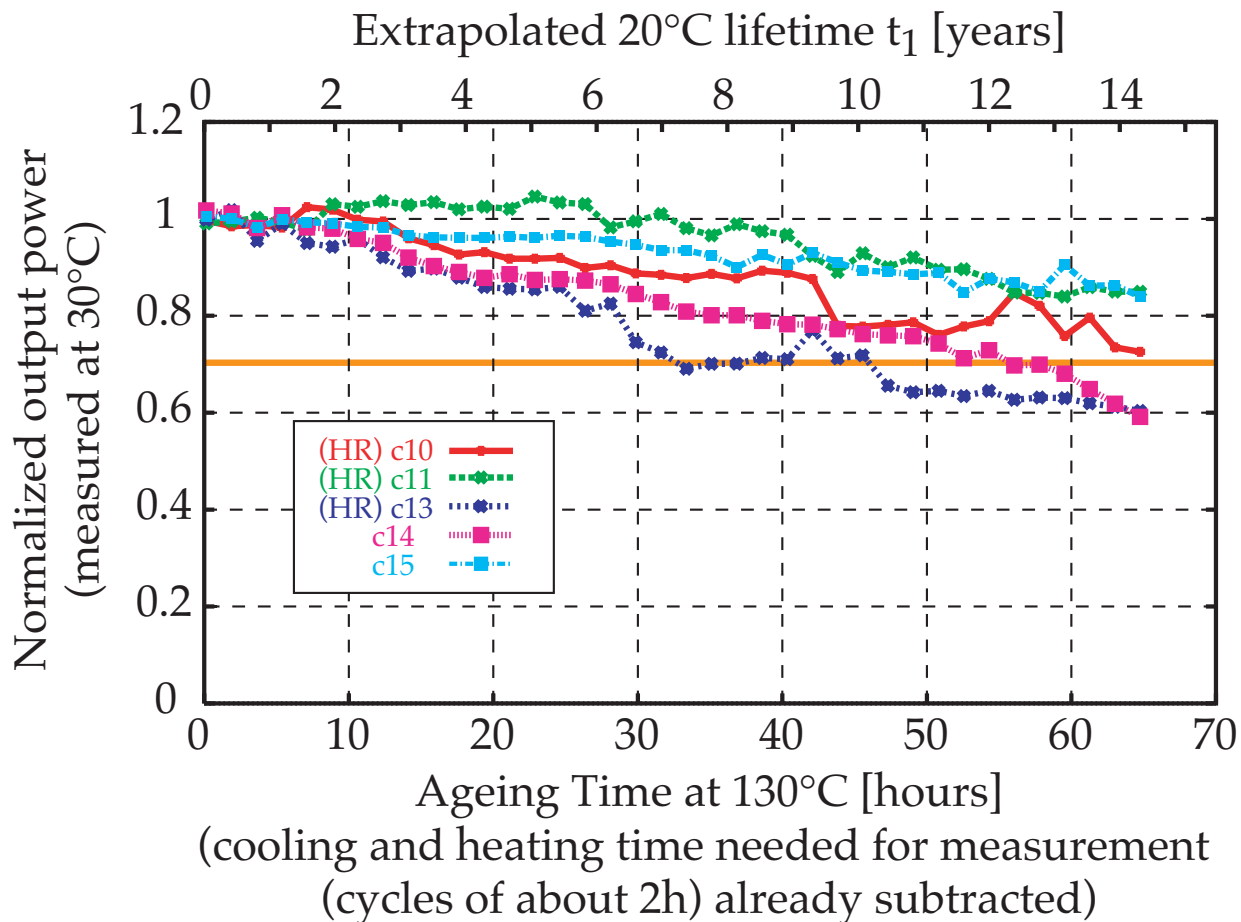
(using 100°C for example it will take 5 times longer)

80°C

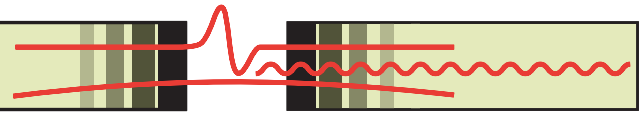
17



Ageing at 130°C: results

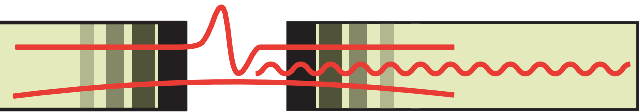


Alpes Lasers

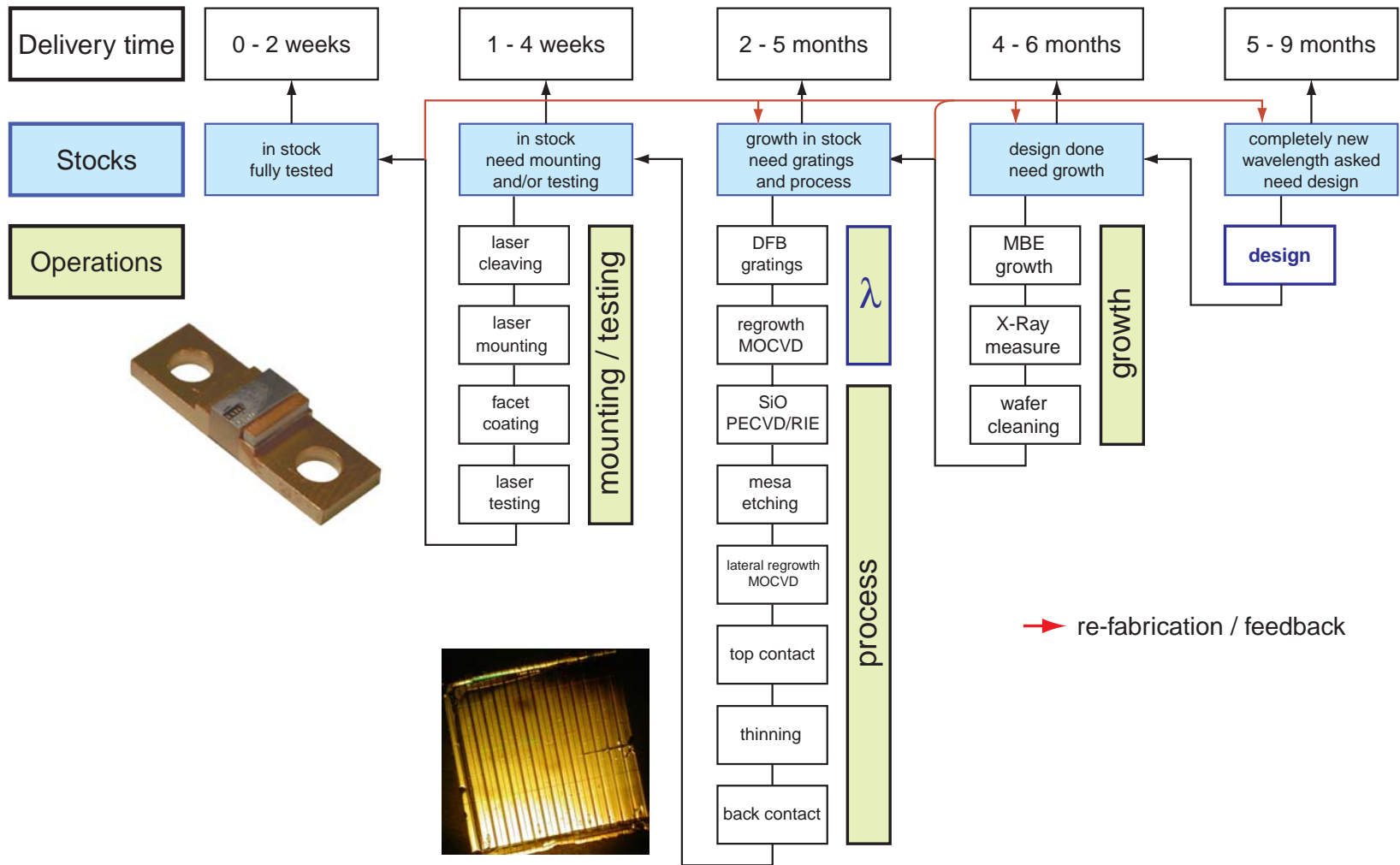


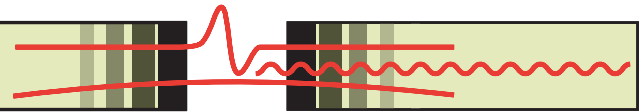
Production



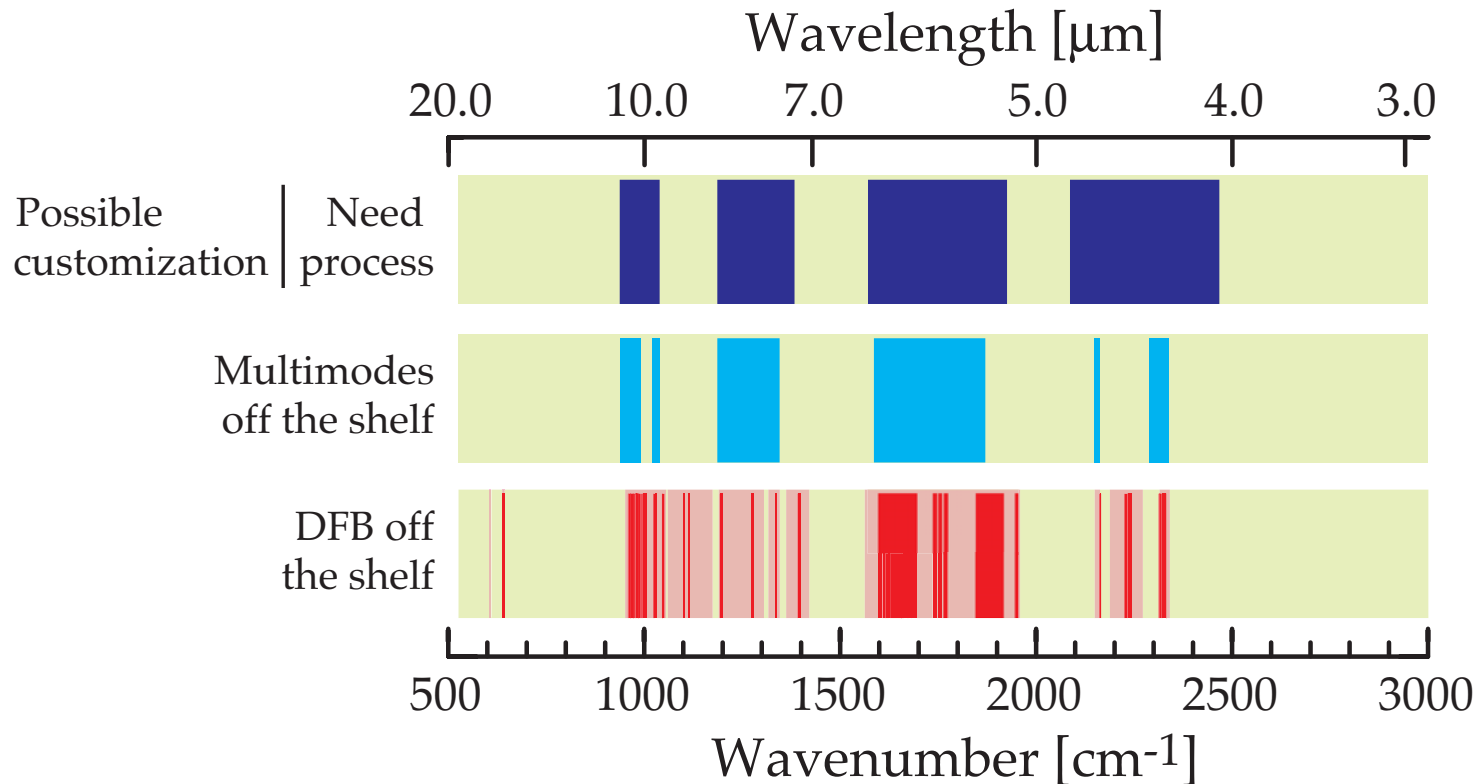


Production line

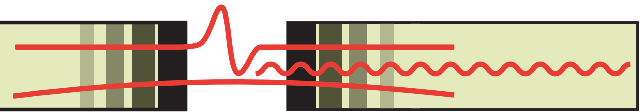




Production - lasers off the shelf

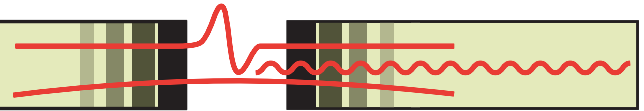


for an up to date wavelength listing, contact us at: <http://www.alpeslasers.ch>



List of products - prices

Type	Duty-cycle	Operating temp.	Product name	Power	Linewidth	Tunability	Off the shelf	Built to order	100+
DFB	pulsed	RT	RT-HP-DFB-2-X	> 2 mW	< 330 MHz	0.4%	11 kEUR	28 kEUR	
			RT-HP-DFB-5-X	> 5 mW			13.5 kEUR		
	cw	LN ₂	LN2-CW-DFB-2-X	> 2 mW	< 3.5 MHz	0.4%	23.5 kEUR	50 kEUR	
	cw	RT	RT-CW-DFB-2-X	> 2 mW	< 3.5 MHz	0.4%	available end 2004		
FP	pulsed	RT	RT-HP-FP-10-X	> 10 mW	1 - 4 %	N/A	6 kEUR		
	pulsed	LN ₂	LN2-HP-FP-150-X	> 150 mW	1 - 4 %	N/A	20 kEUR		
	cw	RT	RT-CW-FP-5-X (only at 9.1 μm)	> 5 mW	1 - 4 %	N/A	17 kEUR		



Conclusion / outlook

Available products

- pulsed DFB QCL on Peltier cooler in the range of $4.3\mu\text{m}$ to $16.5\mu\text{m}$
- LN_2 continuous-wave DFB QCL in the range of $4.6\mu\text{m}$ to $10\mu\text{m}$
- continuous-wave FP on Peltier cooler at $9.1\mu\text{m}$

Soon available

- THz sources (LN_2)

Available end 2004

- continuous-wave DFB on Peltier cooler
(already demonstrated: T. Aellen, S. Blaser, M. Beck, D. Hofstetter, J. Faist, and E. Gini, Appl. Phys. Lett. **83**, p.1929, 2003)
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