High power and single frequency quantum cascade lasers for chemical sensing

Stéphane Blaser

final version: http://www.alpeslasers.ch/Conference-papers/QCLworkshop03.pdf

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Collaborators

Alpes Lasers

Yargo Bonetti
Lubos Hvozdara
Antoine Muller
Guillaume Vandeputte
Hege Andersen

This work was done in collaboration with the University of Neuchâtel

Marcella Giovannini
Nicolas Hoyler
Mattias Beck
Jérome 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

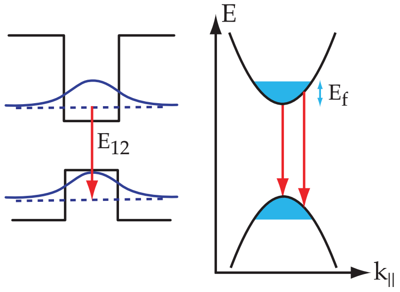
- > 30 man-years experience
- 7 patents on QCL technologies

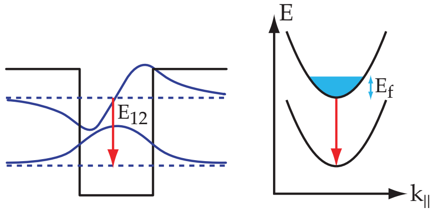
- > 150 devices sold
- > 50 customers

- 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

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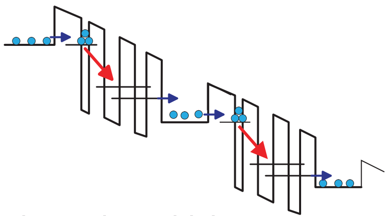
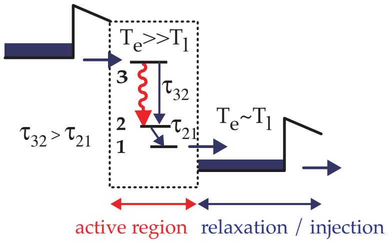
Quantum cascade lasers

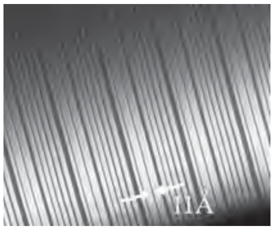
- **Cascade**
  - each e- emits N photons



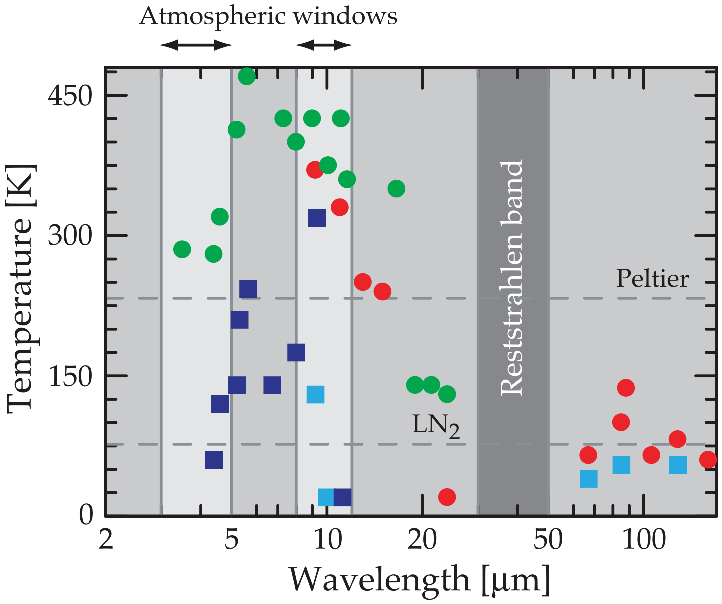
- **Active region / injector**
  - active region ➔ population inversion which must be engineered
  - injector ➔ avoid fields domains and cools down the electrons



- **MBE**
  - growth of thin layers
  - sharp interfaces



State of the art: QCL performances



- Good Mid-IR coverage
- Terahertz promising

Data:

MIR	FIR
Uni Neuchâtel	NEST Pisa
Alpes Lasers	MIT
Bell Labs	Uni Neuchâtel
Thales	
TU Vienna	
Northwestern Uni	
W. Schottky / TU Munich	

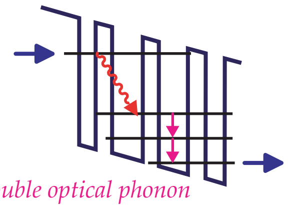
Designs

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).



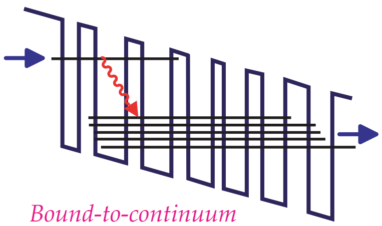
Double optical phonon resonance

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

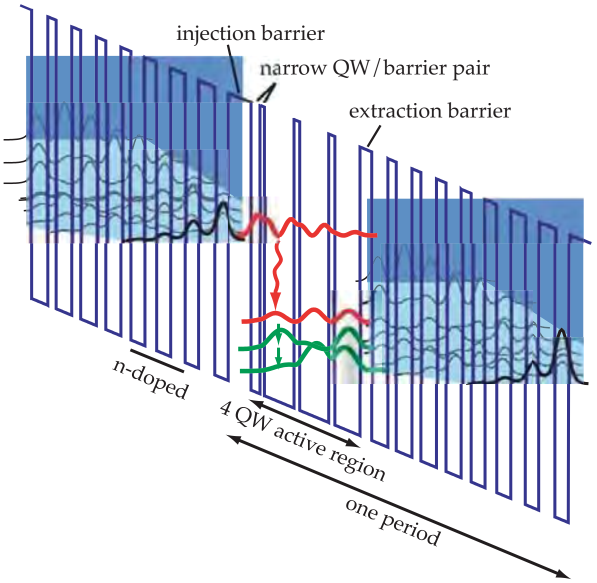
Two-phonon structure at 8 µm

Based on two-phonon resonances design

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

Grown by MBE on InP substrate

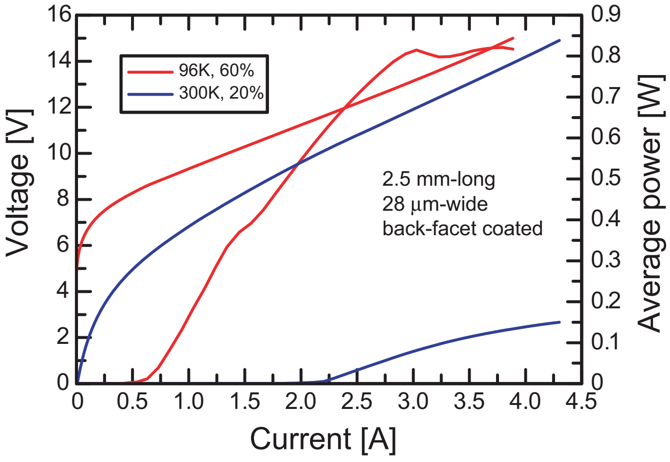
35 periods



41, 16, **8**, 53, **10**, 52, **11**, 45, **21**, 29, **15**, 28, **16**, 28, **17**, 27, **18**, 25, **21**, 25, **26**, 24, **29**, 24

High average power FP QCL

RT-HP-FP-150-1266



Characteristics

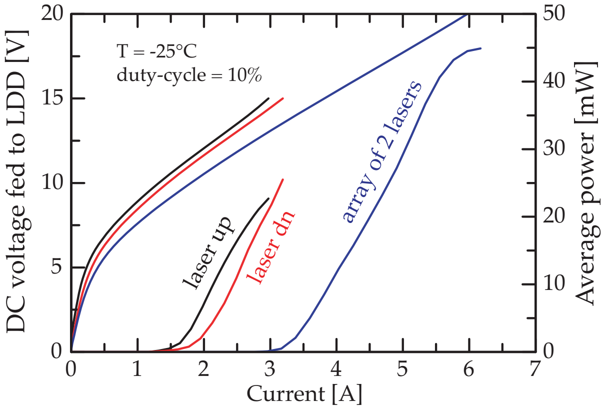
$\lambda = 7.9\ \mu m$

@300K: Average power:
P = 150 mW
threshold current:
I_{th} = 2.1A (j_{th}=3.0 kA/cm^2)

@96K : P = 0.82 W (60% dc)
I_{th} = 0.51A (j_{th}=0.75 kA/cm^2)
CW: P = 300mW
(j_{th} = 0.78 kA/cm^2)

Array of lasers

DUAL-RT-HP-FP-40-1266



Characteristics

both lasers: 1.5 mm-long, 28 µm-wide
λ ≈ 7.9 µm
T = -25°C, duty-cyle = 10%

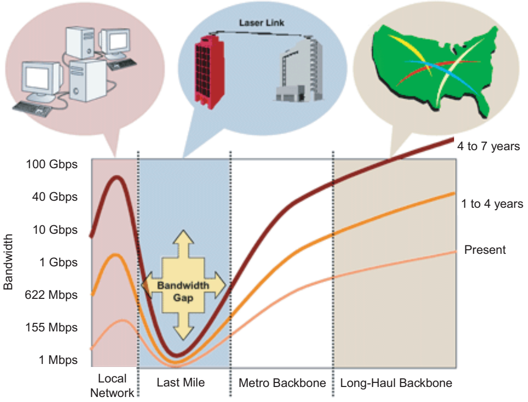
laser	Average power	I_{th} [A]	j_{th} [kA/cm^2]
up	25.4 mW	1.8	4.29
dn	22.6 mW	1.6	3.81
array	44.9 mW	3.4	4.05

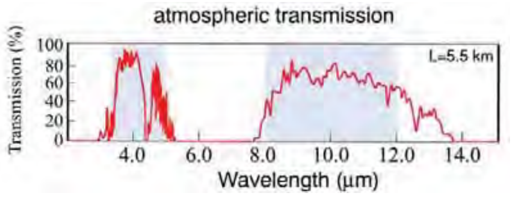
- Total power ≈ 90% (P_1+P_2)
- Total threshold current ≈ I_1+I_2

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 λ = 1.55 μm)





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

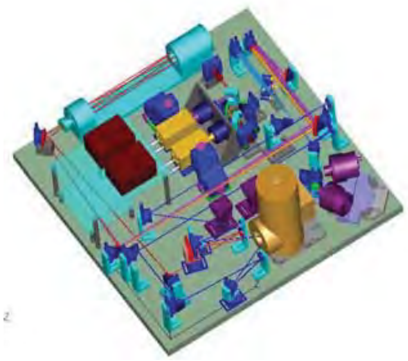
single mode

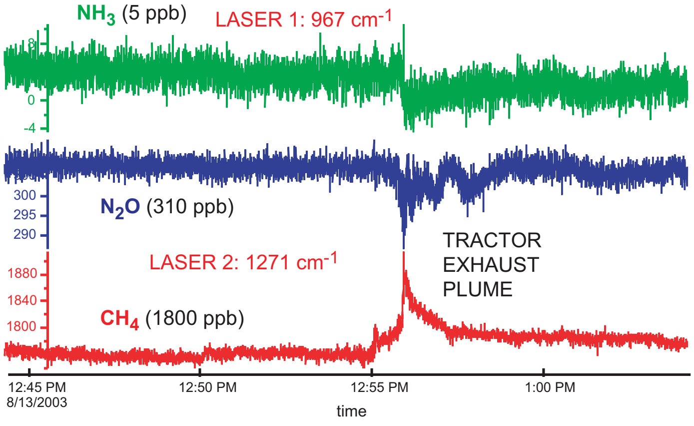
continuous-wave

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

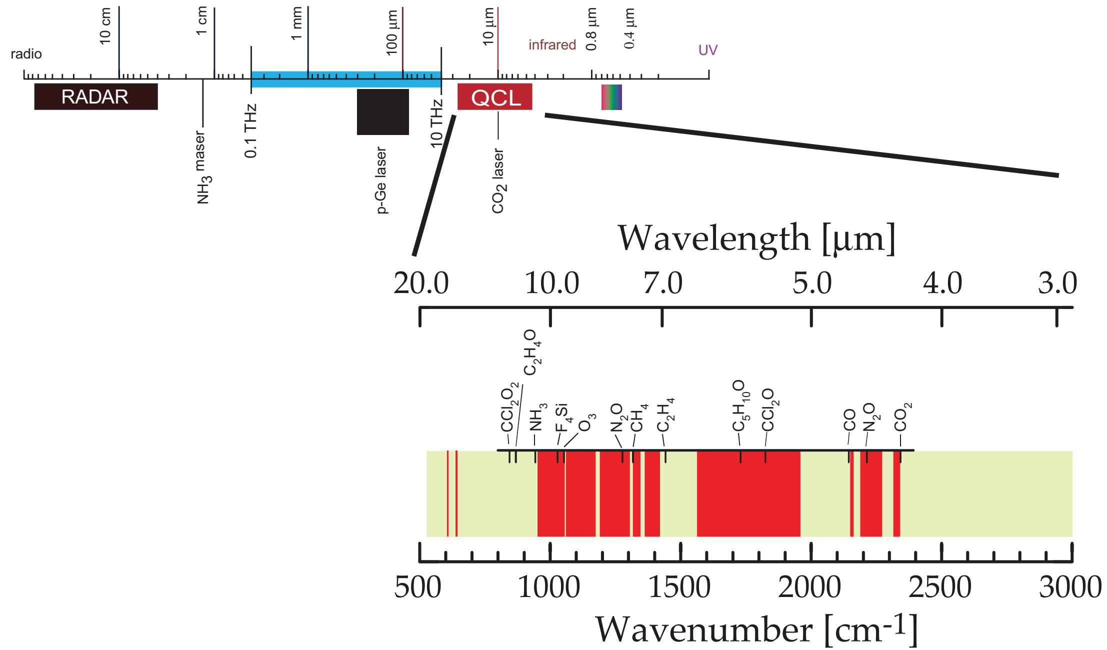




Two QC-lasers from Alpes:
2 to 6 gases (CH_4, N_2O, NH_3)
56 m cell path length
Detector options

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

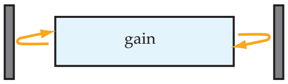
Spectrum covered by Alpes Lasers dfb QCLs



Single-mode operation: distributed-feedback QCLs

How does a DFB work?

Fabry-Pérot laser:

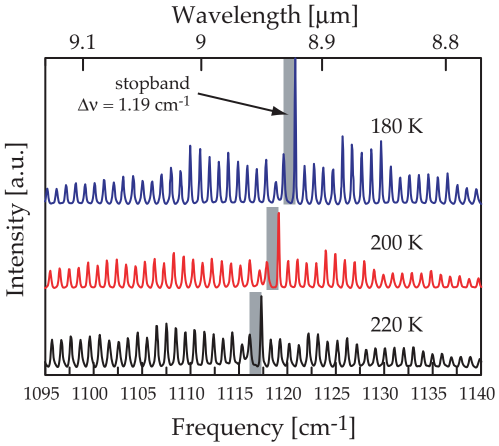


Amplified light bounces in the cavity

DFB:
periodic grating => waves coupling
=> high wavelength selectivity

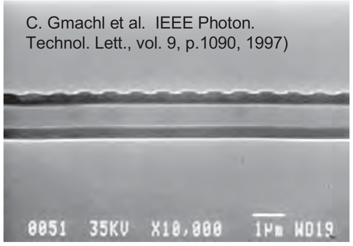
complex-coupled DFB:

- lasing mode closest to the stopband
- stopband ≈ coupling strength



Distributed-feedback technologies

D. Hofstetter et al., Appl. Phys. Lett., vol. 75, p.665, 1999)



C. Gmachl et al. IEEE Photon. Technol. Lett., vol. 9, p.1090, 1997)

Grating on the surface (open-top)

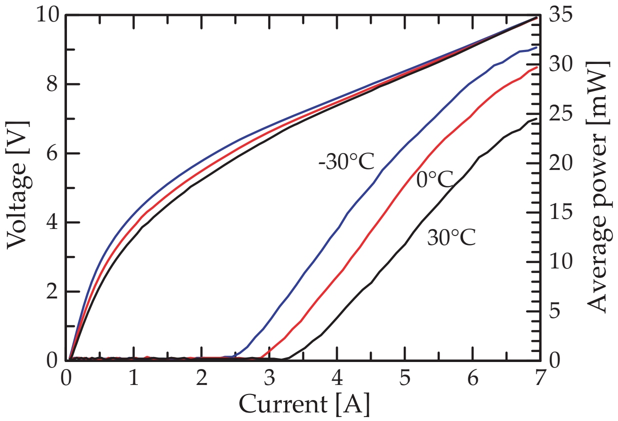
- one MBE run (no MOCVD)
- high peak power (large stripes) but low average power
- optical losses due to metalization

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 8.35μm with InP top cladding



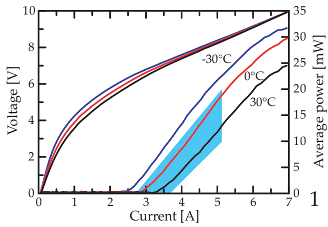
Characteristics

3mm-long, 28μm-wide laser
$\lambda \approx 8.35$ μm

@-30°C: Average power (2% dc):
P = 32 mW (1.6 W peak power)
threshold current:
I_{th} = 2.44 A (j_{th} = 2.9 kA/cm^2)

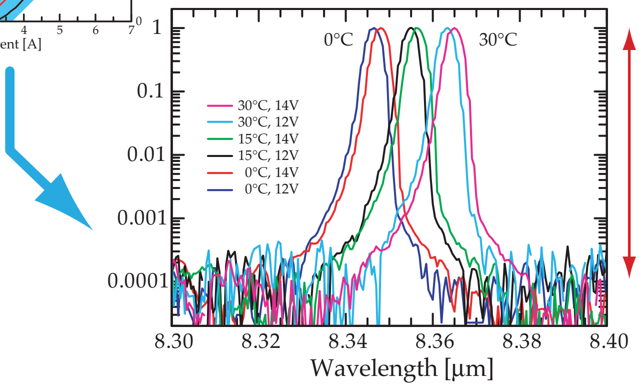
@30°C : P = 25 mW (1.25W peak power)
I_{th} = 3.2 A (j_{th} = 3.8 kA/cm^2)

High average power DFB QCL RT-HP-DFB-20-1200



Characteristics

Entire tuning range:
$\Delta\nu$ = 5.7 cm^{-1} at 1197 cm^{-1} (0.47%)
(1195.2 cm^{-1} (8.367 μm) at 30°C to 1200.9 cm^{-1} (8.327 μm) at -30°C)

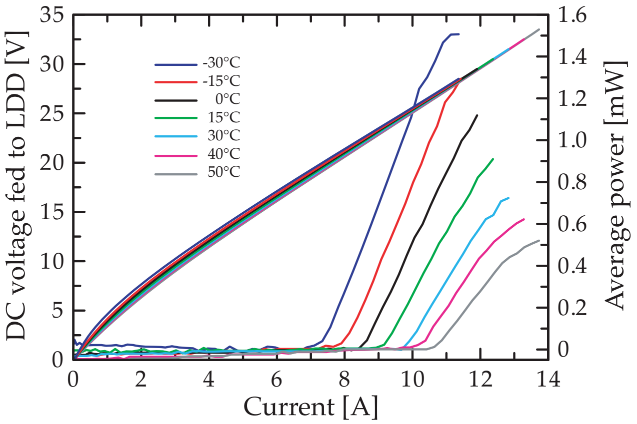


40 dB (limited by the grating spectrometer)

Long-wavelength (λ≈16.4μm) B2C DFB QCL RT-P-DFB-1-608

Laser based on a bound to continuum design, λ ≈ 16.4 μm

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



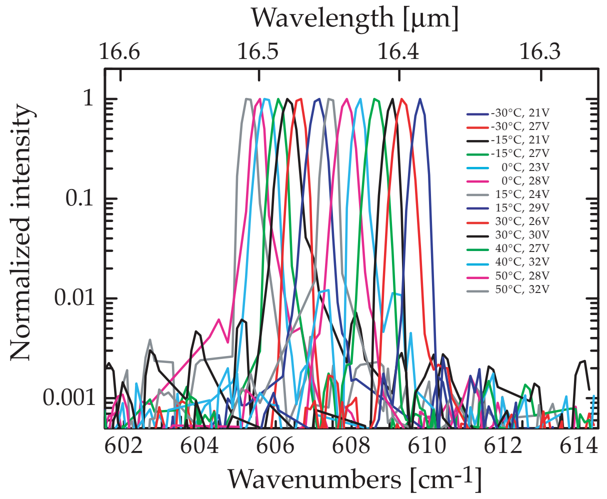
Characteristics

3 mm-long, 44μm-wide laser
λ ≈ 16.4 μm

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

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

Long-wavelength (λ≈16.4μm) B2C DFB QCL RT-P-DFB-1-608



Characteristics

3mm-long, 44μm-wide laser
λ ≈ 16.4 μm

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

Tuning range:
Δν = 4.5 cm^{-1} at 608 cm^{-1} (0.7%)

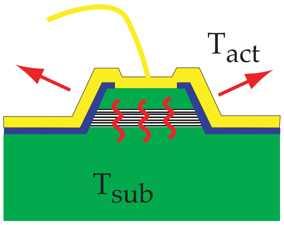
(605.76 cm^{-1} (16.51 μm) at 50°C to
610.30 cm^{-1} (16.38 μm) at -30°C)

How does a DFB tune?

How does a DFB tune?

Tuning always due to thermal drift

(carrier effects can be neglected!)

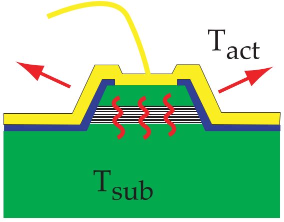


wavelength selection : $\lambda = 2 \cdot n_{eff} \cdot \Lambda_{grating}$

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

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

How does a DFB tune?



Active region heating:

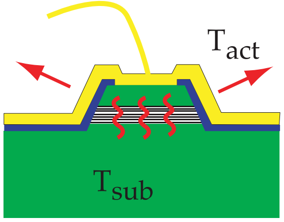
$$T_{act} = T_{sub} + I \cdot U \cdot \delta \cdot R_{th} \left(+ I_{DC} U_{DC} \cdot R_{th}\right)$$

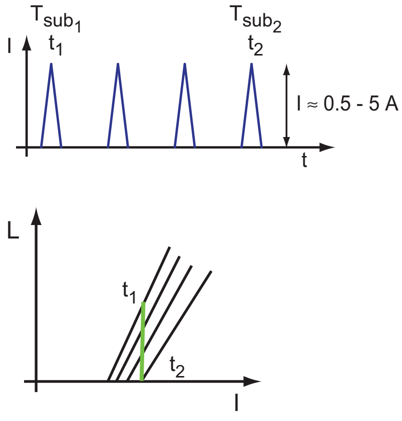
$$\Delta T = T_{act} - T_{sub}$$

If ΔT = 100°C ⇨ 100% chance of laser-destruction (thermal stress)
= 60°C ⇨ depends of mounting / laser -> dangerous
= 30°C ⇨ 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)





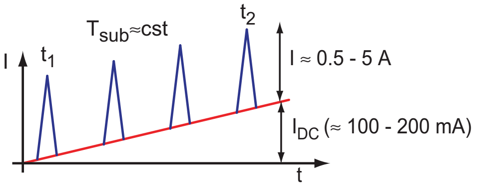
tuning coefficient :

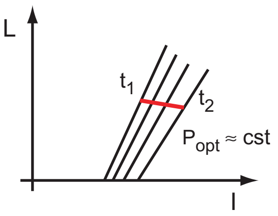
$$\frac{1}{\lambda}\frac{\Delta\lambda}{\Delta T_{sub}} = \frac{1}{n_{eff}}\frac{\Delta n_{eff}}{\Delta T_{sub}} \approx [6-7]\cdot 10^{-5}\ K^{-1}$$

ΔT ≈ 60°C => -0.4% Δν/ν @ 0.01Hz

Tuning by DC bias-induced heating

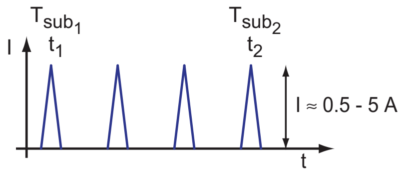
by DC bias-induced heating

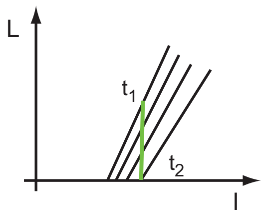




$$R_{th} = \frac{\Delta T}{V_{device} \cdot I_{DC}}$$

by changing T$_{sub}$

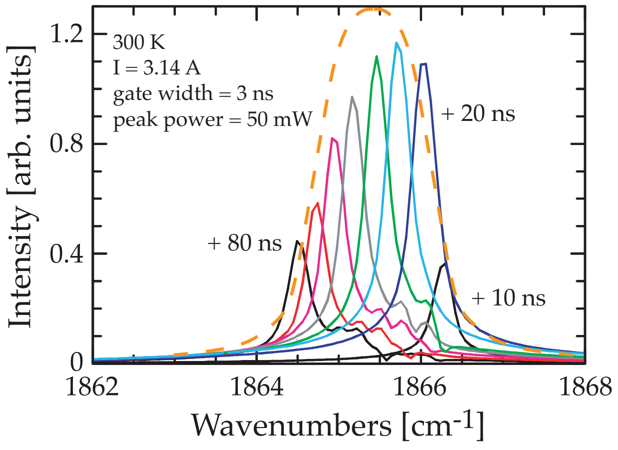




$\Delta T \approx 30°$C => -0.2% $\Delta\nu/\nu$ @ >1kHz

$\Delta T \approx 60°$C => -0.4% $\Delta\nu/\nu$ @ 0.01Hz

Thermal chirping during pulse

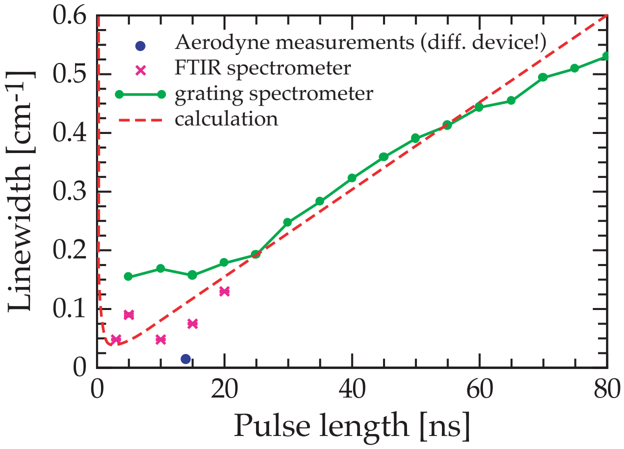


drift with time: 0.03 cm^{-1}/ns (high dissipated power)

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

Faist et al., Appl. Phys. Lett. 70, p.2670 (1997)

Pulse length dependence of linewidth



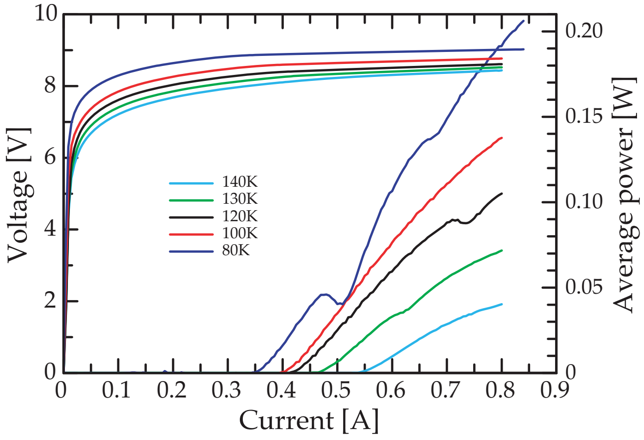
Need for a good compromise:
- too long: limited by thermal chirping
- too short: limited by the time evolution of the lasing mode

⇨ fundamental limits

⇨ for narrower linewidth: cw operation

Hofstetter et al., Opt. Lett. 26, p.887 (2001)

CW operation at λ ≈ 6.73μm LN2-CW-DFB-100-1485



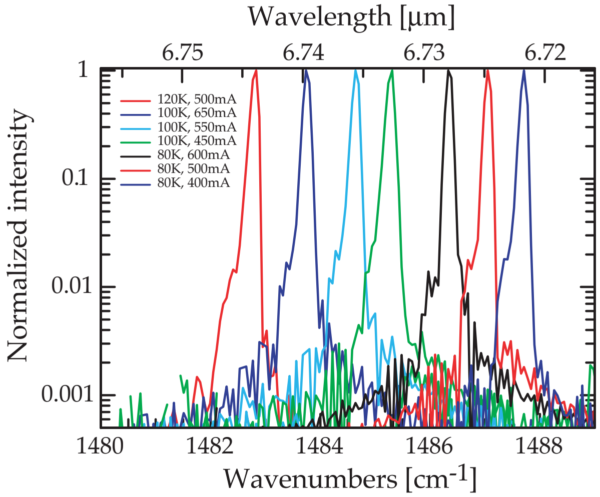
Characteristics

1.5 mm-long, 23 μm-wide laser
CW operation at λ ≈ 6.73 μm

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

I_{op} < 0.8 A
U_{op} < 9 V

CW operation at λ ≈ 6.73μm LN2-CW-DFB-100-1485



Characteristics

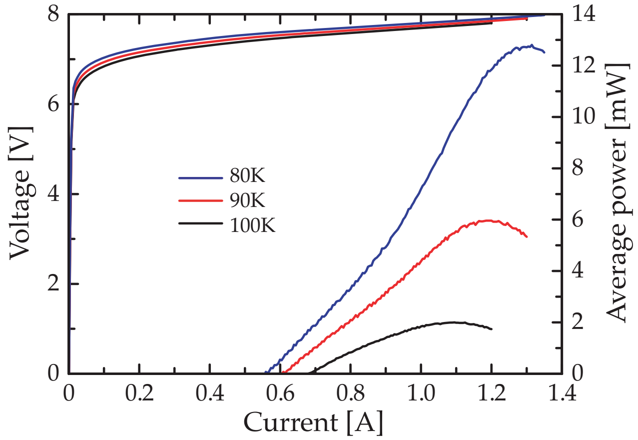
1.5 mm-long, 23 μm-wide laser
CW operation at λ ≈ 6.73 μm

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

Tuning range:
Δν = 4.9 cm^{-1} at 1485 cm^{-1} (0.33%)

(1482.8 cm^{-1} (6.744 μm) at 120K to
1487.7 cm^{-1} (6.722 μm) at 80K)

CW operation at λ ≈ 4.60μm LN2-CW-DFB-10-2171



Characteristics

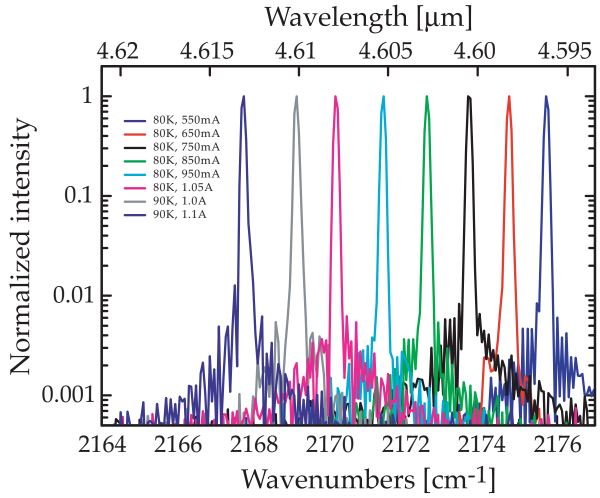
1.5 mm-long, 21 μm-wide laser
CW operation at λ ≈ 4.60 μm

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

I_{op} < 1.1 A
U_{op} < 8 V

CW operation at $\lambda \approx 4.60\mu m$

LN2-CW-DFB-10-2171



Characteristics

1.5 mm-long, 21 µm-wide laser
CW operation at $\lambda \approx 4.60$ µm

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

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

(2167.7 cm^{-1} (4.613 µm) at 90K to
2175.7 cm^{-1} (4.596 µm) at 80K)

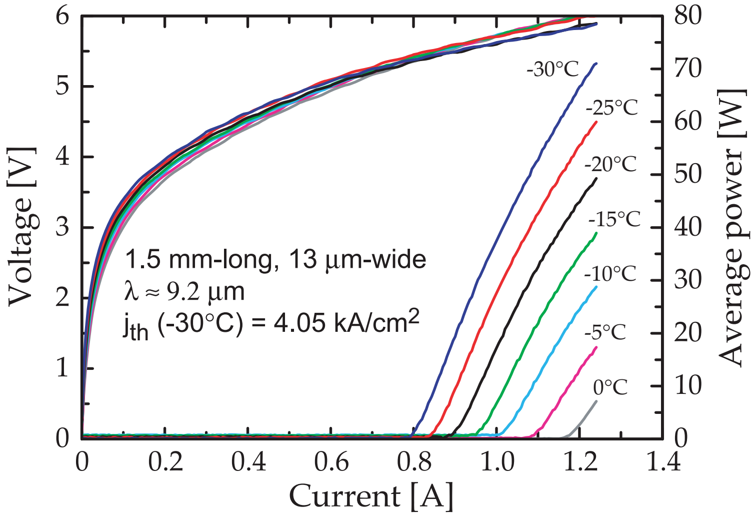
Future:

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

terahertz sources

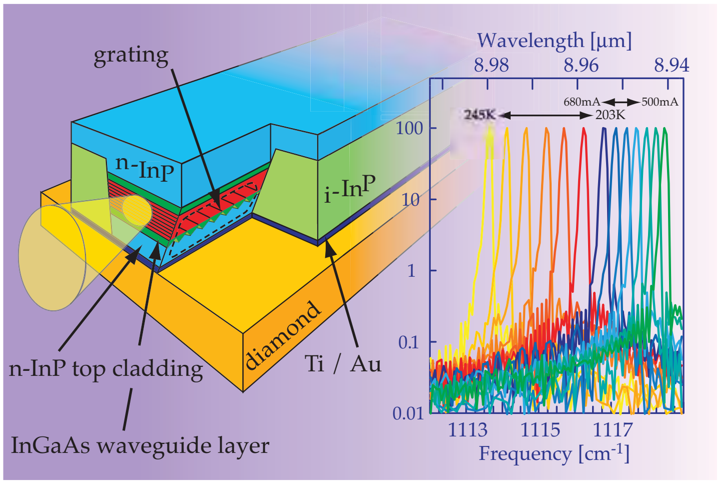
Continuous-wave FP QCL on Peltier

RT-CW-FP-50-1080



$I_{op} < 1.2$ A
$U_{op} < 6$ 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.

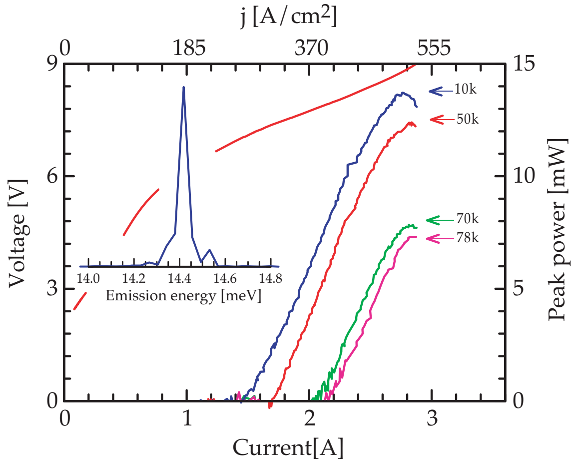
Terahertz applications:

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

Terahertz sources

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

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



Characteristics

THz QC laser: $\lambda \approx 87\ \mu m$

2.7mm-long, 200µm-wide laser

back-facet coated

@10 K: Peak power (2.5% dc):

P = 14 mW

threshold current density:

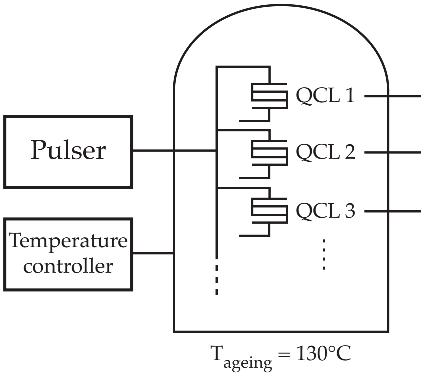
j_{th} = 267 A/cm^2

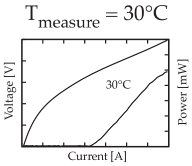
pulsed operation up to 78K

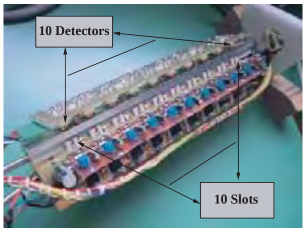
CW operation up to 30 K

Reliability of the devices

Reliability of the devices: ageing







Ageing: theory

Conversion of lifetime using Arrhenius type relation: t ~ 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)

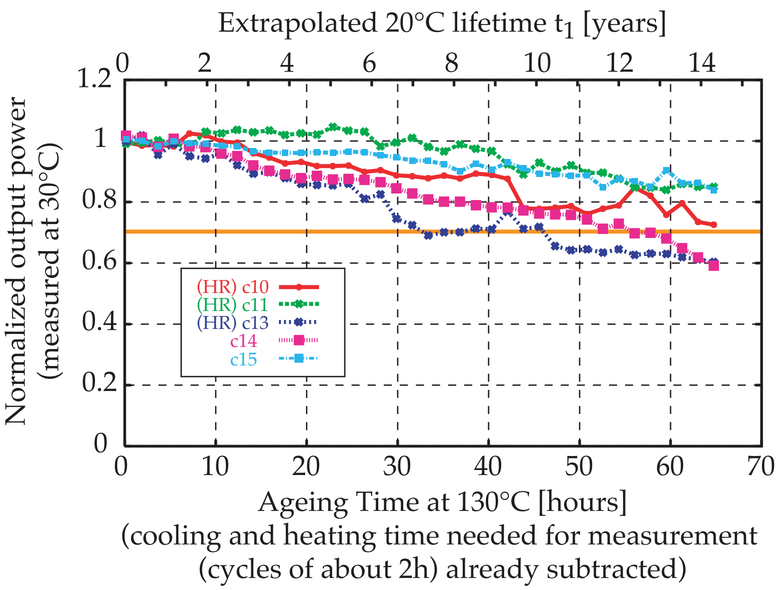
The room temperature lifetime t_1 (at T_1 = 20°C and 70% of initial power) can be extrapolated by :

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

with t_0 is the measured lifetime at the ageing temperature T_0 (here 130°C = 403K).

(using 100°C for example it will take 5 times longer)
80°C 17

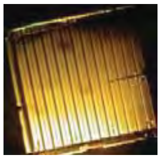
Ageing at 130°C: results



Production

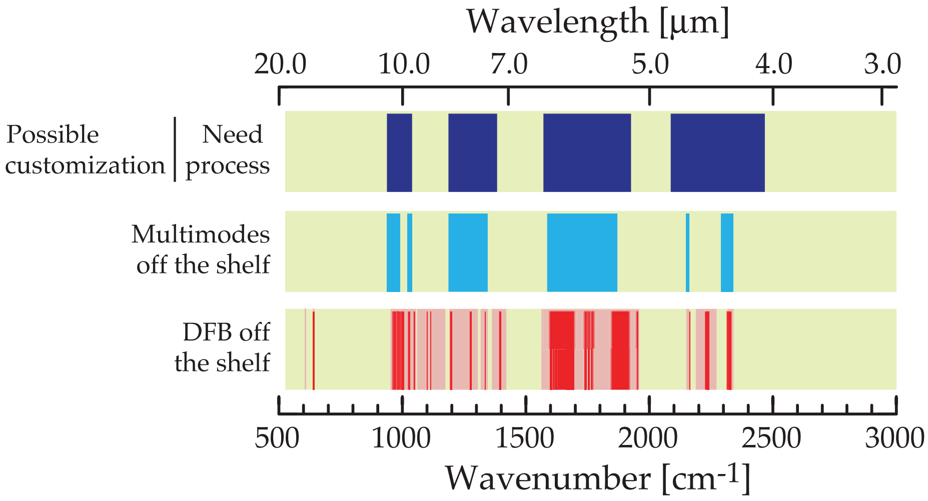
Production line

Delivery time	0 - 2 weeks	1 - 4 weeks	2 - 5 months	4 - 6 months	5 - 9 months
Stocks	in stock fully tested	in stock need mounting and/or testing	growth in stock need gratings and process	design done need growth	completely new wavelength asked need design
Operations		**mounting / testing** laser cleaving laser mounting facet coating laser testing	**λ** DFB gratings regrowth MOCVD **process** SiO PECVD/RIE mesa etching lateral regrowth MOCVD top contact thinning back contact	**growth** MBE growth X-Ray measure wafer cleaning	**design**



→ re-fabrication / feedback

Production - lasers off the shelf



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

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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		

http://www.alpeslasers.ch

Conclusion / outlook

Available products

- pulsed DFB QCL on Peltier cooler in the range of 4.3µm to 16.5µm
- LN$_2$ continuous-wave DFB QCL in the range of 4.6µm to 10µm
- continuous-wave FP on Peltier cooler at 9.1µm

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)