Continuous-wave single-mode quantum cascade lasers

Stéphane Blaser
The team

Sophie Brunner
Emmanuel Gentilhomme
Stéphane Goeckeler
Sandra Hofmann
Sandrine Huin
Dr. Lubos Hvozdara
Dr. Antoine Muller
Lim-Vitou Nam
Alexandre Netuschill
Dr. Hideaki Page
Vanessa Piot
Guillaume Vandeputte

University of Neuchâtel:
Marcella Giovaninini
Nicolas Hoyler
Jérôme Faist
Why CW single-mode (DFB) QCL?
Spectroscopy: NO sensor

Research grade RT-CW-DFB-QC lasers at Alpes Lasers
cw RT DFB at $\lambda = 1830$ cm$^{-1}$

Linewidth
heterodyne measurement

Recent progress:
RT-CW-DFB for NO line $\lambda = 1900$cm$^{-1}$
countermeasures: High power FP QCL at $\lambda = 2230$ cm$^{-1}$ (4.5µm)
TEC-CW-DFB QCL based NO OA-ICOS Sensor

TEC-CW-DFB QCL based OA-ICOS (off-axis integrated cavity output spectroscopy) sensor for NO.

QC laser:
3mm-long, 14µm-wide back-coated, mono/bimode
$T = -21^\circ\text{C}$
tuning range: 1835.3 to 1836.4 cm$^{-1}$

D. Yarekha, J. Faist et al.
Y. Bakhirkin, F. Tittel et al.
Averaged second harmonic scan of the ICOS cavity output for the NO line P(11.5) at 1835.57 cm\(^{-1}\) (5.45 µm) for a NO concentration of 23.7 ppbv, with fitting curve (data acquisition time = 1s)

\[\text{-> minimum NO detection limit} = 0.7 \text{ ppb in 1s}\]

2f NO concentration measurements for 3 different concentrations in flow conditions.

Activities

**Production-DFB**
- RT-P-DFB
- LN2-CW-DFB
- RT-P-FP

**Custom-DFB**
- HP-RT-P-DFB
- New wavelength RT-P-DFB
- New wavelength LN2-CW-DFB

**Research Activities**
- **RT-CW-DFB**
  - Cryogenic-DFB-THz
  - Very special devices

Inquire

Check [www.alpeslasers.ch](http://www.alpeslasers.ch)

On request

4.2 to 17µm

EU contract / On request
Design: bound-to-continuum

**Bound-to-continuum**
(patent n° wo 02/019485A1)
- transition from a bound state to a miniband
- broad miniband, spread oscillator strength
- broadening the gain by a transition to a “continuum”
  - allows fabrication of single frequency devices over a wide range
Processing

- MBE active region based on bound-to-continuum design (0.5% strain-compensated InGaAs/InAlAs)
- DFB grating: periods of $\Lambda = 830.3 - 861.3$ nm
- InP top-cladding by MOVPE
- thick (3-4µm) electroplating gold layer
- 1.5 mm-long lasers mounted epi-side up
- no back-facet coating
CW DFB QCL on TE-cooler at 5.46µm

Max. single-mode operating temperature: \( T = 27\,^\circ\text{C} \)
\( T_0 = 170\,\text{K} \)

Threshold current density = 1.26 kA/cm\(^2\) (-30°C)

- 1.5mm-long, 18µm-wide laser
- no coating

• best device: CW up to 30°C
CW DFB QCL on TE-cooler at 5.46µm

- 1.5mm-long, 18µm-wide laser
- no coating

Single-mode emission between -30 and 25°C

SMSR > 30 dB
(resolution limited by FTIR)

Tuning range $\Delta \nu = 12 \text{ cm}^{-1}$
at 1830cm$^{-1}$ (0.65%)
Subthreshold spectra

Typical measurement at 80K in cw around 960 cm\(^{-1}\):

- Stopband clearly resolved: \(\Delta \nu = 2.85\) cm\(^{-1}\)
- Lasing mode on the right side of the stopband (cw)
- \(\kappa = \pi n_{\text{eff}} \Delta (1/\lambda) \approx 29\) cm\(^{-1}\)
  \[\Rightarrow \kappa l \approx 4\] for 1.5mm-long laser
CW DFB QCL on TE-cooler at 5.46µm

- 1.5mm-long, 18µm-wide laser
- no coating

Single-mode emission between -30 and 25°C

\[ \nu = \nu_0 + \beta \nu T_{\text{sink}} + R_{\text{th}} \beta \nu P_{\text{elec}} \]

Tuning: \( \beta = -8.79 \cdot 10^{-5} \text{ K}^{-1} \)

\( G_{\text{th}} = 369 \text{ W} / \text{Kcm}^2 \)

\( R_{\text{th}} = 10.04 \text{ K/W} \)

All measured lasers:
Average tuning: \( \beta = -8.87 \cdot 10^{-5} \text{ K}^{-1} \) (-8.33 \cdot 10^{-5} K^{-1} to -9.37 \cdot 10^{-5} K^{-1})
Average thermal conductance: \( G_{\text{th}} = 431 \text{ W} / \text{Kcm}^2 \) (359 to 525 W / Kcm²)
Heterodyne measurement with 2 RT-CW-DFB QCL

QCL1:
1.5mm-long, 18\(\mu\)m-wide,
\(T = -10\)C, \(I = 460\)mA \(\sim 1831.0\) cm\(^{-1}\)

QCL2:
1.5mm-long, 14\(\mu\)m-wide,
\(T = -30\)C, \(I = 316\)mA \(\sim 1831.0\) cm\(^{-1}\)
Linewidth measurement (no frequency modulation)

Heterodyne beat 5.9 MHz FWHM
Why CW single-mode (DFB) QCL?
Spectroscopy: NO sensor

Research grade RT-CW-DFB-QC lasers at Alpes Lasers
 cw RT DFB at $\lambda = 1830 \text{ cm}^{-1}$

Linewidth
 heterodyne measurement

Recent progress:
 RT-CW-DFB for NO line $\lambda = 1900 \text{ cm}^{-1}$
 countermeasures: High power FP QCL at $\lambda = 2230 \text{ cm}^{-1}$ (4.5$\mu$m)
CW DFB QCL on TE-cooler at 5.26µm

- 1.5mm-long, 12µm-wide laser
- no coating

Max. single-mode operating temperature: \( T = 20^\circ\text{C} \)
\( T_0 = 115\text{K} \)

Threshold current density = 2.1 kA/cm\(^2\) (-30°C)

- best device: CW up to 20°C
CW DFB QCL on TE-cooler at 5.26µm

RT-CW-DFB-40-1900

- 1.5mm-long, 12µm-wide laser
- no coating

Single-mode emission between -30 and 15°C

Tuning range $\Delta \nu = 12.7 \text{ cm}^{-1}$ at 1900 cm$^{-1}$ (0.67%)

Tuning: $\beta = -8.96 \cdot 10^{-5} \text{ K}^{-1}$

$G_{\text{th}} = 451 \text{ W / K cm}^2$

Suitable for NO detection!

All measured lasers:
Average tuning: $\beta = -9.55 \cdot 10^{-5} \text{ K}^{-1}$ (-8.96 $\cdot 10^{-5}$ K$^{-1}$ to -9.92 $\cdot 10^{-5}$ K$^{-1}$)
Average thermal conductance: $G_{\text{th}} = 445 \text{ W / K cm}^2$ (382 to 513 W / K cm$^2$)
Typical value for pulsed devices: $\beta = -7 \times 10^{-5} \text{ K}^{-1}$

Typical value for CW devices at LN2 temperatures: $\beta = -7 \times 10^{-5} \text{ K}^{-1}$

First CW-DFB (BH) at $\lambda \sim 9.1 \mu\text{m}$ (T. Aellen et al., APL 83, 2003): $\beta = -6.98 \times 10^{-5} \text{ K}^{-1}$

RT-CW-DFB:

First shot $\lambda \sim 5.46 \mu\text{m}$ (S. Blaser et al., APL 86, 2005): $\beta = -9.5 \times 10^{-5} \text{ K}^{-1}$ ($G_{\text{th}} = 360 \text{ W / Kcm}^2$)

Razeghi: $\lambda \sim 4.8 \mu\text{m}$ (J. Yu et al., APL 87, 2005): $\beta = -8.6 \times 10^{-5} \text{ K}^{-1}$ ($G_{\text{th}} = 347 \text{ W / Kcm}^2$)

This work $\lambda \sim 5.46 \mu\text{m}$: $\beta = -8.87 \times 10^{-5} \text{ K}^{-1}$ ($G_{\text{th}} = 431 \text{ W / Kcm}^2$)

This work $\lambda \sim 5.26 \mu\text{m}$: $\beta = -9.55 \times 10^{-5} \text{ K}^{-1}$ ($G_{\text{th}} = 445 \text{ W / Kcm}^2$)

$\Rightarrow$ larger tuning in CW operation at RT due to:

strain?
thermal dilatation of the grating?
Why CW single-mode (DFB) QCL?
Spectroscopy: NO sensor

Research grade RT-CW-DFB-QC lasers at Alpes Lasers
cw RT DFB at $\lambda = 1830 \text{ cm}^{-1}$

Linewidth
heterodyne measurement

Recent progress:
RT-CW-DFB for NO line $\lambda = 1900 \text{ cm}^{-1}$
countermeasures: High power FP QCL at $\lambda = 2230 \text{ cm}^{-1}$ (4.5µm)
High-power QCL on TE-cooler at 4.5µm

- 4.77 mm-long, 24µm-wide
- HR back-facet coating (Al₂O₃ / Au / Al₂O₃)

At -30°C:
Max peak power = 4.2 Watts (at 1%dc)
Max average power = 190 mW (at 8.3% dc)
jth = 1.3 kA/cm²

At 80K:
Max peak power = 12.4 Watts (at 1%dc)
Max average power = 0.85 Watts (at 18% dc)
jth = 0.64 kA/cm²
Slope efficiency = 2.4 W/A

Cryostat: collection efficiency of 77% due to parabolic mirror taken into account
High-power QCL on TE-cooler at 4.5μm

Broadening of the emission spectra:
\[ \Delta E = 120 \text{ cm}^{-1} = 14.9 \text{ meV} \]

Energy scale:
4W -> Rabi splitting ~ 10meV
Conclusions

RT-CW-DFB QCL available at ~ 5.46µm and soon as standard products at λ ~ 5.26µm for spectroscopic applications

Heterodyne measurements have shown a linewidth of ~ 4 MHz and allowed a linewidth enhancement factor measurement with high-frequency modulation

High-power FP QCL at λ ~ 4.5µm for countermeasures applications have shown more than 4 W peak power at -30C (TE-cooled) and more than 12 W at 80K
High-frequency and linewidth enhancement factor

High-frequency measurements up to 990 MHz

Linewidth enhancement factor $\alpha$:

$$\Delta f = \Delta f_{\text{Schawlow-Townes}} (1 + \alpha^2) \quad (*)$$

$\alpha$ can be extracted from the ratio of the intensity of center line and first sideband modes (**) 

distance between sideband and center line is equal to the modulation frequency

increase of the modulation depth $m$ $\rightarrow$ increase of the sideband spectra intensity

---

Modulation frequency at m=0.4

20MHz: not only AC modulation -> chirp due to temperature (low frequency)
Modulation frequency at m=0.8

Even high modulation shows quasi-AC modulation only

(less precision with high m)
Linewidth enhancement factor $\alpha$

Measurements:
linewidth enhancement factor close to 0

Theory of QCL: intersubband laser
$\rightarrow$ symmetric gain
$\rightarrow$ carrier-induced refractive index variation should be zero $\rightarrow$ LEF=0

BUT: device self-heating or other mechanisms of refractive index change

Activities: Special production

- Delivery time:
  - 0 - 2 weeks: Stocks in stock fully tested
  - 1 - 4 weeks: in stock need mounting and/or testing
  - 3 - 6 months: growth in stock need gratings and process
  - 6 - 9 months: design done need growth
  - 9 - 18 months: completely new wavelength asked need design

Operations:
- Design
  - Mounting/polishing
  - Laser cleaving
  - Laser mounting
  - Facet coating
  - Laser testing
  - DFB gratings
  - Regrowth MOCVD
  - SiO PECVD/RIE
  - Mesa etching
  - Lateral regrowth MOCVD
  - Top contact
  - Thinning
  - Back contact

Production line:
- Re-fabrication / feedback