Room-temperature continuous-wave single-mode quantum cascade lasers

Stéphane Blaser
Team - collaborations

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- Dr. Stephan Jochum
- Dr. Stefan Hansmann
Outline

Introduction
QCL and state of the art (CW operation)
Why CW single-mode (DFB) QCL?

Research grade RT-CW-DFB-QC lasers at Alpes Lasers
heterodyne measurement at $\sim = 1830$ cm$^{-1}$
nitric oxide spectrometer at $\sim = 1900$ cm$^{-1}$

Recent progress:
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countermeasures: High power FP QCL at $= 2140$ cm$^{-1}$ (4.67$\mu$m)
Fundamental concepts

• **Intersubband transition**
  - unipolar, narrow gain
  - photon energy depends on layer thickness and can be tailored

• **Cascade**
  - multi-quantum well structure with numerous layers
  - each e- emits N photons
Quantum cascade lasers

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

- **DFB grating**
  - single-mode design

- **Bonding**

Yearly number of papers mentioning “quantum cascade” (source: ISI web of Science)
Applications

Infrared gas spectroscopy

• Trace gas detection
• Remote sensing
• Environment control, monitoring
• Quality analysis, industrial process

Medical diagnostics

• Breath analysis (50’000 ER visits/y in USA because of asthmatic crisis)
• Glucose monitoring (5.5 millions diabetics in EU)
• Non-invasive techniques

Telecommunications

• Free-space transmissions
Applications: security & defense

Energy deposition

Gas sensing (security in airports, public areas, military)

Teraherz Imaging

- Imaging through packages
- Scanning and sensing
- Non-invasive chemical tomography

• • Illumination
• Countermeasures
  - missile defeat systems
  - missile warning system testers

• Drug/explosive detection
• Chemical/biological agents detection
Why CW-RT QCL?

- **Mid-infrared**
  - strong molecules absorptions
  - selectivity (fundamental modes)

- **QCL**
  - high power
  - room-temperature operation

- **Continuous-wave**
  - laser linewidth (< 10 MHz)
  - discrimination of close absorption lines
  - electronics (DC current source instead of pulser)
State of the art of CW operation on TE-cooler

FP CW operation of QC lasers (published):

<table>
<thead>
<tr>
<th>Max. Temp.</th>
<th>Power</th>
<th>BH</th>
<th>epi</th>
<th>thick gold</th>
<th>HR coated</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.1 μm</td>
<td>17mW @ 20°C</td>
<td>x</td>
<td>dn</td>
<td>-</td>
<td>x</td>
<td>M. Beck et al., Science 295 (2002)</td>
</tr>
<tr>
<td>6 μm</td>
<td>446mW@ 20°C</td>
<td>x</td>
<td>up</td>
<td>x</td>
<td>x</td>
<td>A. Evans et al., APL 84 (2004)</td>
</tr>
<tr>
<td>4.8 μm</td>
<td>370mW @ 20°C</td>
<td>-</td>
<td>up</td>
<td>x</td>
<td>x</td>
<td>A. Evans et al., APL 85 (2004)</td>
</tr>
<tr>
<td>4.3 μm</td>
<td>166mW @ 25°C</td>
<td>up</td>
<td></td>
<td>x</td>
<td>x</td>
<td>J. Yu et al., PTL 17 (2005)</td>
</tr>
</tbody>
</table>

Single-mode (DFB) CW operation of QC lasers (published):

<table>
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<tr>
<th>Max. Temp.</th>
<th>Power</th>
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<th>epi</th>
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<tr>
<td>9.1 μm</td>
<td>3mW @ -30°C</td>
<td>x</td>
<td>dn</td>
<td>-</td>
<td>x</td>
<td>T. Aellen et al., APL 83 (2003)</td>
</tr>
<tr>
<td>5.4 μm</td>
<td>13mW @ -30°C</td>
<td>-</td>
<td>up</td>
<td>x</td>
<td>-</td>
<td>S. Blaser et al., APL 86 (2005)</td>
</tr>
<tr>
<td>4.8 μm</td>
<td>155mW @ 20°C</td>
<td>-</td>
<td>up</td>
<td>x</td>
<td>x</td>
<td>J. Yu et al., APL 87 (2005)</td>
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Design: bound-to-continuum

Bound-to-continuum
- bound state to broad miniband
- homogeneous broadening of the gain

allows fabrication of single frequency devices over a wide range

(patent n° wo 02/019485A1)
Processing

- MBE active region based on bound-to-continuum design (0.5% strain-compensated InGaAs/InAlAs)
- DFB grating: periods of \( = 830 - 860 \text{ nm} \)
- InP top-cladding by MOVPE
- thick (3-4\(\mu\)m) electroplating gold layer
- 1.5 mm-long lasers **mounted epi-side up**
- **no** back-facet coating
CW DFB QCL on TE-cooler at 5.46\(\mu\)m

- 1.5mm-long, 18\(\mu\)m-wide laser
- no coating

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

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

- best device: CW up to 30\(^\circ\)C

\begin{align*}
P &= 50\,mW \\
T &= -30\,^\circ C
\end{align*}
CW DFB QCL on TE-cooler at 5.46\(\mu\)m

- 1.5mm-long, 18\(\mu\)m-wide laser
- no coating

Single-mode emission between -30 and 25°C

SMSR > 30 dB
(resolution limited by FTIR)

Tuning range = 12 cm\(^{-1}\)

at 1830 cm\(^{-1}\) (0.65%)
CW DFB QCL on TE-cooler at 5.46 μm

Single-mode emission between -30 and 25°C

Tuning: \[ = -8.79 \cdot 10^{-5} \text{ K}^{-1}\] (all lasers: \(-8.33 \cdot 10^{-5} \text{ K}^{-1}\) to \(-9.37 \cdot 10^{-5} \text{ K}^{-1}\))

Thermal conductance: \[ G_{th} = 369 \text{ W} / \text{ Kcm}^2 \] (all lasers: 359 to 525 W / Kcm²)
Heterodyne measurement with 2 RT-CW-DFB QCL

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

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

Heterodyne beat
5.9 MHz FWHM
Linewidth enhancement factor

- **Theory:**
  linewidth enhancement factor should be 0

- **Measurements:**
  close to 0 at high modulation frequency
  Laser chirping up to \( \sim 80 \text{ MHz} \)
  (thermal crosstalk between refractive index and the dissipated power)
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**CW DFB QCL on TE-cooler at 5.26 m**

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

Max. single-mode operating temperature: \( T = 20^\circ C \)

\( T_0 = 115K \)

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

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

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

Single-mode emission between -30 and 15°C

Tuning range = 12.7 cm⁻¹ at 1900 cm⁻¹ (0.67%)

Tuning:  = -8.96 · 10⁻⁵ K⁻¹

G_{th} = 451 W/ K cm²

Suitable for NO detection!
CW-RT QCL spectrometer for NO

RT-CW-DFB-40-1900

VIGO TE-COOLED DETECTORS

ASTIGMATIC MULTIPASS CELL
76 m (238 passes), 0.5 liters

BEAMSPLITTER

REF CELL LINE LOCK

CW-QC LASER TC-51 COOLER

COMPUTER
3 MHz
A-D D-A

RAMP

ILX LASER DRIVER

NO “DOUBLET”
1900 cm⁻¹

M. Zahniser et al., Aerodyne Research Inc., Billerica (USA)
CW-RT QCL: laser linewidth

Doppler broadened NO spectrum
Laser Line width < 0.0004 cm\(^{-1}\) (12 MHz)

M. Zahniser et al.,
Aerodyne Research Inc., Billerica (USA)
CW-RT QCL: laser mode purity

RT-CW-DFB-40-1900

“BLACK” NITRIC OXIDE SPECTRUM
Laser Single Mode Purity > 99.98%

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

25 days of continuous data without operator attention (6 weeks in total)

TE-cooled laser and detectors
PRECISION 0.3 ppbv Hz^{-1/2}

M. Zahniser et al., Aerodyne Research Inc., Billerica (USA)
Nitric oxide breath test

NITRIC OXIDE IN BREATH IS AN INDICATOR FOR ASTHMA

CWRT-QCL MEASURES BOTH NO and CO₂
RESPONSE TIME 0.5 s
NO 8 ppbv
CO₂ 4.5%

M. Zahniser et al., Aerodyne Research Inc., Billerica (USA)
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MOVPE growth of QCL

Motivation for Metal-organic vapor-phase epitaxy (MOVPE):
• is suitable for InP growth
• widely used for production of epitaxial layer
• is the technology of choice for industrial fabrication
• already demonstrated its suitability for QCL*
• Alpes Lasers recently acquired IPAG (Darmstadt, D)

* References:
L. Diehl et al., to be published in Appl., Phys. Lett.

See talk 6133-05: Gloria Hoefler et al. (last talk of this session)
**MOVPE grown QCL on TE-cooler at 5.6 m**

- 3mm-long, 12 m-wide laser
- Back-facet coating (Al₂O₃ / Au / Al₂O₃)

**Maximum operating temperature:** $T = -5°C$

$T₀ = 84K$

**Threshold current density**

- $= 1.74 \text{ kA/cm}^2 (-30°C)$

**Graph:**

- Voltage [V] vs. DC current [A]
- Power [mW] vs. DC current [A]

- $P = 60 \text{mW}$
- $T = -30°C$
MOVPE grown QCL on TE-cooler at 5.6 m

- 3mm-long, 12 m-wide laser
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High-power QCL on TE-cooler at 4.67 m

Large optical waveguides:

- Reduces losses
- Increases the saturation intensity
- Lower beam divergence: ~ 30° instead of 60° (growth direction)
- Drawback: poorer thermal transport

T. Gresch et al., to be published in PTL
High-power QCL on TE-cooler at 4.67 m

- 4.5 mm-long, 16 m-wide
- HR back-facet coating (Al$_2$O$_3$ / Au / Al$_2$O$_3$)

**T = -30°C**
- Max peak power (at 1%dc) > 5 Watts
- Max average power 350 mW (at 10%dc)
- Threshold current density 1.4 kA/cm$^2$

**T = +30°C**
- Max peak power (at 1%dc) > 3.3 Watts
- Max average power 135 mW (at 8%dc)
- Threshold current density 2.5 kA/cm$^2$
High-power QCL on TE-cooler at 4.67 m

At 80K:
Max peak power > 8 Watts (at 1%dc)
Max average power = 1.17 Watts (at 24% dc)

Maximum operating temperature: 180°C
At 90°C: peak P > 2 W
At 150°C: peak P > 200 mW
Conclusions

RT-CW-DFB QCL available at ~ 5.46 m and at ~ 5.26 m for spectroscopic applications:
Heterodyne measurements showing a linewidth of ~ 4 MHz

Nitric oxide spectrometer @Aerodyne Research with continuous measurements during 6 weeks, laser linewidth < 0.0004 cm\(^{-1}\) and mode purity > 99.98%

MOPVE grown QCL up to -5°C for external cavity systems

High-power FP QCL at ~ 4.7 m for countermeasures applications have shown more than 5 W peak power and 350mW average power at -30C (TE-cooled) / more than 1 W average power at 80K / maximum operating temperature of 180°C