Injectorless Quantum Cascade Lasers

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Acknowledgement

- Gerhard Böhm
- Christoph Huber
- Giuseppe Scarpa
Outline

- QC-laser with and without injector region
- Design of injectorless QC-lasers
- Results
- Summary
Classical concept of QC lasers

Quantum-cascade laser with injection miniband

- transfer of electrons
- working in a wide electric field range
- doping: stable current flow
- suppression of thermal backfilling

- optically passive sections
- thicker active stage (reduced mode-overlap and gain)
QCLs without injector regions

- no optically passive sections
- compact gain regions

Problems to solve:
- how to inject electrons?
- limited electric field range?
- scattering on donor impurities?
- thermal backfilling?
First injectorless QCLs (@ 8-10 µm)

- Former lasers with low performance\(^1\)-\(^3\)
  - high threshold current densities \((J_{th} > 3 \text{ kA/cm}^2, 77 \text{ K})\)
  - limited maximum operating temperature \((T_{max} \approx 200 \text{ K})\)

3\(^{G. Scarpa et al., IEEE Proceedings IPRM, 2002, pp. 735-738\}

- First improvements with a 4-level design and InP/GaInAs waveguide\(^4\)
  - threshold current densities reduced by more than a factor of 3
  - increased maximum operating temperature \((T_{max} > 350 \text{ K})\)

4\(^{A. Friedrich et al., Electron. Lett., 2005, No. 9, pp. 529-531\}
First injectorless QCLs (@ 8-10 μm)

But:
- Restricted wavelength-range ($\lambda \approx 8-10 \ \mu m$)
- High operating voltages ($U_{th} (300K) > 13 \ \text{V}$)
- Thermal backfilling of lower laser state?

- First improvements with a 4-level design and InP/GaInAs waveguide
  - threshold current densities reduced by more than a factor of 3
  - increased maximum operating temperature ($T_{\text{max}} > 350 \ \text{K}$)

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4A. Friedrich et al., Electron. Lett., 2005, No. 9, pp. 529-531
Improved concepts

- **Aims:**
  - $\lambda < 8 \, \mu\text{m}$
  - avoid thermal backfilling
  - reduced operating voltage

- **Design concept:**
  - five-level staircase
  - no injector miniband

- **Double or triple LO-Phonon resonant**
Design of active region

Active section (in nm): 2.8/4.0/1.3/5.0/1.0/6.5/1.0/1.2/1.4/2.8

- 5-level concept
  (5QW active region)
- Strain compensation:
  $\text{Al}_{0.635}\text{In}_{0.365}\text{As} / \text{Ga}_{0.4}\text{In}_{0.6}\text{As}$
  $\rightarrow \Delta E_c \approx 690 \text{ meV}$

$\lambda \approx 6.8 \mu\text{m}$
Design of active region

Active section (in nm): 2.8/4.0/1.3/5.0/1.0/6.5/1.0/1.2/1.4/2.8

- n = 6.5×10^{16} cm^{-3}
- Layers where radiative transitions take place are left undoped

\( \lambda \approx 6.8 \mu \text{m} \)

1 period, 27 nm

96 kV/cm
Design of active region

Increased electric field: triple LO-phonon resonant condition

- Improvements:
  - double / triple LO-phonon design
  - vertical transition
  - increased $\mu_{43}$
  - decreased $\mu_{42}$, $\mu_{53}$
  - shorter wavelength
QCLs without injector miniband

Concept: 5-level staircase

+ no need for a bridging miniband
+ no large optically passive sections
+ compact gain regions

Problems solved:
✓ how to inject electrons
✓ thermal backfilling
✓ scattering on donor impurities
✓ limited electric field range
Structure and Processing

<table>
<thead>
<tr>
<th>Layer Description</th>
<th>Thickness</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate n-InP</td>
<td>0.8 µm</td>
<td>n-InP</td>
</tr>
<tr>
<td>2.5 µm n-InP</td>
<td>2.5 µm</td>
<td>n-InP</td>
</tr>
<tr>
<td>AR: 40 - 60 periods</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 µm n-GaInAs</td>
<td>0.5 µm</td>
<td>n-GaInAs</td>
</tr>
<tr>
<td>0.2 µm n++-GaInAs</td>
<td>0.2 µm</td>
<td>n++-GaInAs</td>
</tr>
</tbody>
</table>

$V_{th} \propto N_p$

- Facets uncoated
- Mounting on copper-heatsink
- Wire bonding

Ti/Pt/Au contact-pad

Facets uncoated
Mounting on copper-heatsink
Wire bonding
Results

Pulsed operation: 250 Hz, 250 ns

- $\lambda \approx 6.8 \, \mu m$
- AR: 60 periods
- $N_s = 6.2 \times 10^{10} \, \text{cm}^{-2}$
- $L = 4 \, \text{mm}$
- $W = 26 \, \mu m$

$J_{th} \approx 0.15 \, \text{kA/cm}^2 (77 \, \text{K})$

$J_{th} \approx 1.65 \, \text{kA/cm}^2 (300 \, \text{K})$

$T_{\text{max}} = 420 \, \text{K}$
Results

Further Reduction of doping sheet density and number of periods (40) in AR

\[ J_{th} \approx 1.2 \text{ kA/cm}^2, \ U_{th} \approx 10 \text{ V} \]

Doping sheet density:
\[ 2.5 \times 10^{10} \text{ cm}^{-2} \]

Limit, because \( T_{max} \) only 310 K

Current density (kA/cm\(^2\))
Doping in active region (1*10\(^{10}\) cm\(^{-2}\))

L=3.5 mm, T=300 K
Summary

- **Injectorless (Staircase) QCLs realized**, based on:
  - five-level staircase
  - double/triple LO-phonon resonant tunneling injection
  - no need for injector miniband
  - no large optically passive sections

- **Results**
  - reduced wavelength ($\lambda_{300K} \approx 6.8 \, \mu m$)
  - exceedingly small $J_{th}$ at low temperatures
  - high temperature operation: $T_{max} \approx 420 \, K$
  - 1.2 kA/cm$^2$ (10V) at 300K → comparable to usual QCLs