Cavity length and ridge width scaling of long-wavelength ($\lambda \sim 14 \, \mu m$) Quantum Cascade lasers

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Outline

- High-performance long-wavelength ($\lambda \sim 14 \, \mu m$) Quantum Cascade (QC) lasers
  - Cavity length scaling and single-mode operation
  - Ridge width scaling and threshold dependence on ridge width
- Summary
Long-wavelength ($\lambda \geq 12 \, \mu m$) QC laser: Application

- Application of long-wavelength ($\lambda \geq 12 \, \mu m$) lasers:
  - Detection of BTEX (benzene, toluene, ethylbenzene, and xylenes), which have harmful effects on the central nervous system and causes cancer.

Absorption spectra of BTEX molecule

(Strongest absorption lines: 12~16 $\mu m$)
Uranium enrichment determination on $^{235}$U in UF$_6$ gas

Absorption spectra of the $^{235}$UF$_6$ (1) and $^{238}$UF$_6$ (2) molecules in the $v_3$ absorption band

$\lambda \sim 14 \, \mu m$ QC laser: Active core design

- Diagonal optical transition
- Two phonon – continuum depletion
  - Fast depopulation by two LO-phonon resonance.
  - Efficient electron extraction by the level continuum spanning the active region and the injector

**Conduction band diagram**

$(In_{0.53}Ga_{0.47}As/ In_{0.52}Al_{0.48}As)$
Spectra of a 2.8-mm-long, 38-µm-wide laser, from 80K to 370K in pulsed mode

Current-tuning spectra range: 13.3~14.1 µm (covers the strong absorption lines of Toluene at ~13.7 µm)

Spectra at different current densities at room temperature
λ ~14 μm QC laser:
Light-Current-Voltage (LIV) characteristics

Performance at room temperature, 300K:

- Low threshold current density: 2.0 kA/cm²
- Peak power: 336 mW
- Slope efficiency: 375 mW/A

LIV measurement of a 2.8-mm-long, 38-μm-wide laser
Threshold current density of 38 μm wide QC lasers with different cavity lengths (1.9 mm, 2.8 mm, and 3.8 mm)

\[ J_{th} = J_0 e^{T/T_0} \]

- High \( T_0 \approx 310 \text{ K} \)
- Over a large temperature range (240-390 K)
- Demonstrate successful prevention on thermal backfilling and thermal activation leakage
- High-performance long-wavelength ($\lambda \sim 14 \ \mu m$) Quantum Cascade (QC) lasers
- Cavity length scaling and single-mode operation
- Ridge width scaling and threshold dependence on ridge width
- Summary
Cavity length scaling: Single mode operation

- Short cavity: increased gain discrimination

  \[ \Delta \nu = \frac{c}{2 \cdot n \cdot l} \]

Gain margin ratio vs. Cavity length of lasers at \( \sim 5.3 \, \mu m \)

Mode-hop free tuning of a 110-\( \mu m \) ultrashort cavity QC laser at \( \sim 5.3 \, \mu m \)

Long-wavelength QC laser:

- A natural narrower gain spectrum.
- Stronger mode discrimination, due to an improved GMR.

Mode competition and gain spectra of 0.25mm long lasers at ~ 5.3 µm and ~ 13.9 µm.
Cavity length scaling: Single mode operation

- Single-mode operation by ultra-short cavities

Laser spectrum from a 0.29 mm long laser with HR-coated back facet, at 132% threshold current in pulsed mode at 80 K.

Single-mode operation of a 0.18 mm long laser with HR-coated back facet at pulsed mode at varying heat sink temperatures.
Cavity length scaling: Single mode operation

- **Mode hop**

Continuous tuning range is limited by FSR.

Single-mode operation of a 0.25 mm long laser.

Free spectrum range (FSR):  
\[ \Delta \frac{1}{\lambda} = \frac{1}{2 \cdot n \cdot l} = 6.09 \ cm^{-1} \]

Continuous tuning range: 5.5 cm\(^{-1}\)
High-performance long-wavelength ($\lambda \sim 14 \, \mu m$) Quantum Cascade (QC) lasers

Cavity length scaling and single-mode operation

Ridge width scaling and threshold dependence on ridge width

Summary
Ridge width scaling

- Ridge-width scaling → affects confinement factor and waveguide loss

![Simulation of confinement factor, waveguide loss, and threshold current density dependence on ridge width](image)

\[ J_{th} = \frac{\alpha_w + \alpha_m}{g \cdot \Gamma} \]

(Left) Two-dimensional simulation of confinement factor, waveguide loss, and threshold current density dependence on ridge width
Ridge width scaling

- Ridge-width dependence of threshold current density

Threshold current density of 1.5 mm long lasers with different ridge widths

Ridge width above 20 μm: threshold insensitive to ridge-width.
Below 20 μm: threshold increases by ~ 25% as ridge width decreases from 20 μm to 14 μm
Ridge width scaling

- Laser ridges by dry etching $\rightarrow$ vertical sidewalls
- Uniform current injection and uniform sidewall confinement
- Improved threshold for $<20$ $\mu$m wide ridges

Two-dimensional simulation of confinement factor, waveguide loss, and threshold current density dependence on ridge width
A ~14 μm QC laser design based on a diagonal optical transition and “two-phonon-continuum” depletion shows a low threshold of 2.0 kA/cm² at 300 K, and a high characteristic temperature $T_0 \sim 310$ K over a wide temperature range from 240 K to 390 K.

The natural narrow gain spectrum of long-wavelength lasers enables large mode discrimination with short cavities. Single mode operation was achieved up to 280 K by 0.25mm long short cavity, with a continuous tuning range of 5.5 cm⁻¹.

Ridge-width dependence of threshold current density is significant for < 20 μm wide lasers at ~ 14 μm. Dry etching techniques for ridge fabrication is promising for improving the performance of narrow-ridge lasers.
Appendix

SEM picture of a ~14um wide ridge
Characteristic temperature dependence on ridge width

Different $T_0$ in the low temperature range (e.g., $T < 200K$) and the high temperature range (e.g., $T > 200 K$), due to saturation of gain coefficient.

Gain coefficient:

$$g = \tau_2 \left(1 - \frac{\tau_1}{\tau_{21}}\right) \frac{4\pi \varepsilon_0^2}{\lambda_0 \varepsilon_0 n L_p} \frac{1}{2\gamma_{21}}$$