Mid-IR distributed feedback interband cascade lasers and their application for detection of CH$_4$

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Why Mid-IR Lasers?

- Molecules possess strong fundamental vibration-rotation lines in the mid-IR
- Mid-IR improves sensitivity by orders of magnitude over near-IR spectroscopy
- There is less spectral interference in the mid-IR

**Planetary science payoff is very high**—
- Atmospheric chemistry
- Hydrocarbon signatures at 3–4 µm & biogenic gases throughout the mid-IR important for life detection
- Possible precursors to molecules of biological relevance important for prebiotic chemistry (e.g. ethane, $C_2H_4$, HCN, HC$_3$N)
- Isotopic ratios can be obtained

For JPL and NASA, the interest is mainly in planetary and Earth science.
What is Interband Cascade (IC) Laser?

cascade process —
» high efficiency, high output power
» uniform injection of carriers over every stage
» lower carrier concentration required for threshold, thus lower loss

interband transition —
» circumvents fast phonon scattering, but faces non-radiative Auger recombination

type-II quantum wells (QWs) —
» facilitates interband tunneling for cascade process
» excellent carrier confinement because of band-gap blocking
◆ Sb-based III-V QW structures —
  » lattice constant near 6.1 Å grown on GaSb
  » quality of GaSb substrate is not yet as good as GaAs and InP
◆ interband transition in type-II QWs —
  » allows for wide wavelength tailoring range
  » alleviates problem of Auger recombination with reduced wave-function overlap between transition states
  » possibility of suppressing Auger losses through quantum engineering, challenging with inaccuracies of material parameters
  » can have benefits from strain effect in QWs
◆ MBE growth —
  » Very complicated structure with more than 2000 layers and >15 hour growth time
  » Some uncertainty and roughness in interfaces
  » Requiring precise control of layer thickness and composition; changes of ±1 Å can shift the lasing wavelength out of a molecular resonance
◆ Device fabrication —
  » typically processed into relatively broad-area laser without facet coating
  » epilayer-side-up mounting onto a Cu sheet
Current JPL Laser Status in terms of Max. $T$
(compared to open literature as of 2/2004)

$III-V$ Sb-based mid-IR diode lasers reported in literature and $J$ - JPL laser
Typical distributed feedback (DFB) IC laser structure

- Thin top-cladding InAs/AlSb SL
  - Facilitate the integration of DFB gratings into the laser without the need of deep etching
  - Use SiO$_2$ layers for insulation and edge metal contacts to minimize the loss
  - In-plane conductivity is much higher than the vertical one, leading to excellent lateral current injection

SEM image of a DFB laser. The grating was formed with e-beam writing and RIE etching into the top cladding layer.
Distributed feedback (DFB) IC Lasers near 3.3 µm

- Single-mode DFB lasers were observed at temperatures up to 175 K in cw mode
- wavelength can be tuned with current at a rate of ~0.05 nm/mA
- output power >1 mW, enough for gas sensing

- DFB mode is determined by grating period Λ
- temperature tuning coefficient ~0.2 nm/K
- both DFB and FB modes exist at certain temperatures and currents
- two degenerate DFB modes

Distributed feedback IC Lasers near 3.5 µm

- Single-mode DFB lasers were observed near 3.5 µm
- Wavelength can be tuned with current at a rate of ~0.03 nm/mA
- Output power >1 mW, enough for gas sensing

- DFB mode is determined by grating period Λ
- Temperature tuning coefficient ~0.2 nm/K
- Both DFB and FB modes exist at certain temperatures and currents
Detection of CH4 using DFB IC lasers

Scan 6  5/5/2004
Device A, ca. 140K, 53 mA
2 mbar methane, 4 cm cell, 295K

Scan 13  5/8/2004
Device B, ca. 150K, 70.3 mA
2 mbar methane, 4 cm cell, 295K

Threshold
50 mA

62.8 mA

Threshold
65.4 mA

76.7 mA
Summary

- Single-mode DFB IC lasers have been made near 3.3 and 3.5 µm
- Continuous wave operation has been demonstrated at temperatures up to 175 K
- DFB IC lasers have been applied for the detection of trace gases such as CH4

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