Development of Efficient Mid-IR Interband Cascade Lasers for Chemical Sensing

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Why Mid-IR Lasers?

Detection limits using diode laser spectroscopy

Molecule	*ppb*	mid-IR (λ)	*ppb*	Near-IR (λ)
H2O	*2.0*	5.94 μm	*60*	1.39 μm
CO2	*0.13*	4.23 μm	*3000*	1.96 μm
CO	*0.75*	4.6 μm	*500*	2.33 μm
NO	*5.8*	5.25 μm	*60000*	1.8 μm
CH4	*1.7*	3.26 μm	*600*	1.65 μm
HCl	*0.83*	3.4 μm	*150*	1.79 μm
H2OC	*8.4*	3.55 μm	*50000*	1.93 μm
NH3	*0.8*	10.3 μm	*800*	1.5 μm

[Bomse, *et al.*, Proc. SPIE **1681**, 138 (1992); and in www.swsciences.com]

Features of semiconductor laser spectroscopy

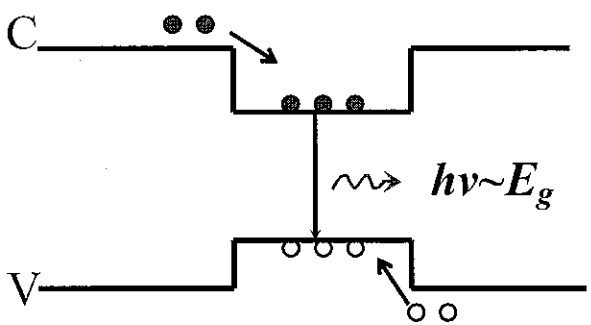
- **high sensitivity and selectivity**
- **fast response & remote sensing capability**
- **low-power consumption & high efficiency**

- Many 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

Many applications —

- Environmental monitoring
- Medical diagnosis/therapeutics
- Eeal-time industrial process controls
- Atmospheric chemistry
- Explosives and leaks detection
- 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_3N)
- Isotopic ratios can be obtained, important markers in biology, geology, medicine, whether and climate

What are the Challenges for Mid-IR Lasers?



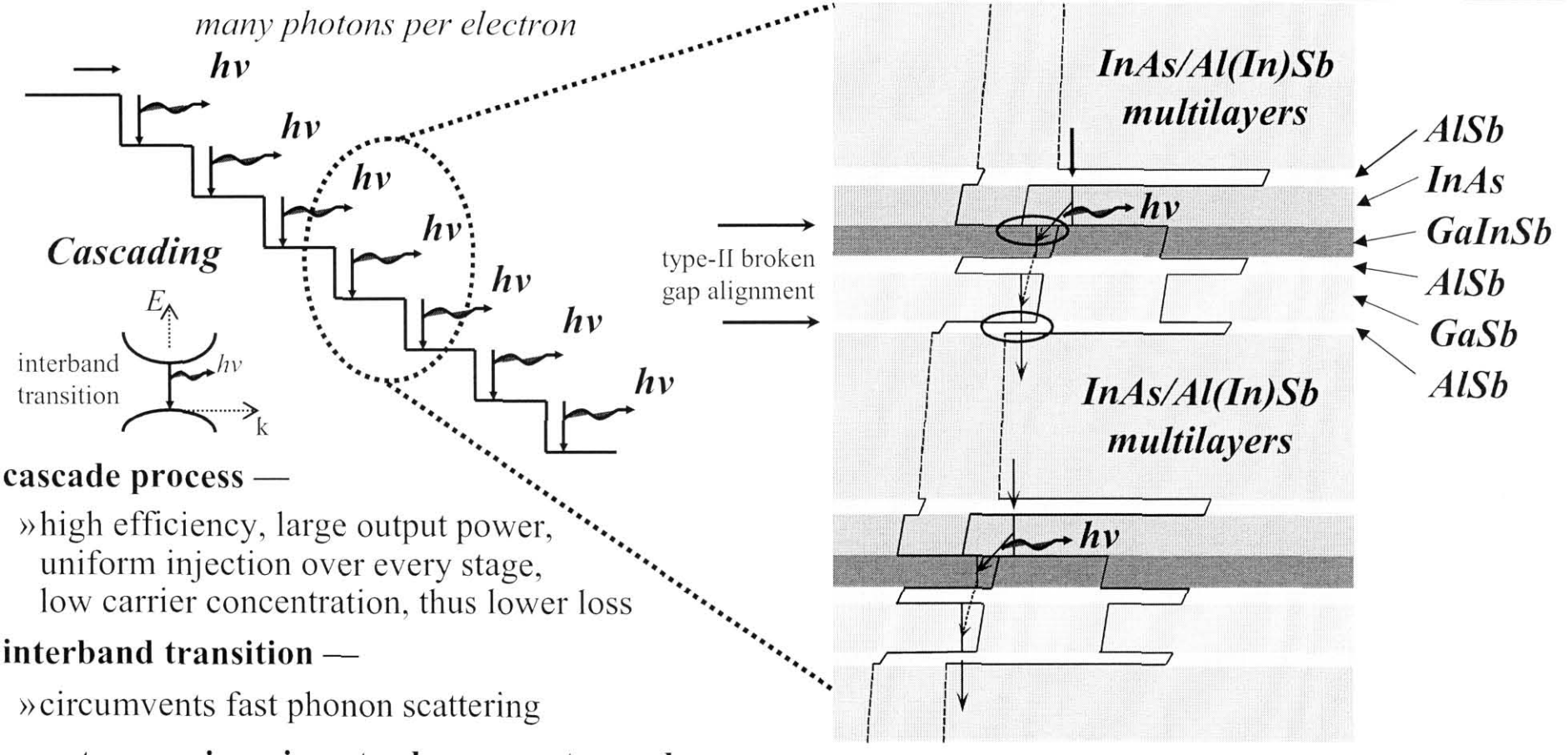
- Electrons & holes combine to give photon emission
- Light emission wavelength $\lambda \propto 1/E_g$

➡ **Mid-IR lasers require narrow E_g materials**

- **Narrow E_g materials are *hard to grow* and *hard to process* into devices**
- **Visible & near-IR lasers are well established**
  - » Large commercial investment drivers (consumer products, optical commun.)
  - » Negligible market thus far for longer wavelength lasers
- **Semiconductor lasers develop other problems as λ increases**
  - » Non-radiative losses increase rapidly
  - » Inadequate electrical confinement
  - » Poor efficiency in utilizing bias voltage
  - » Free carrier absorption loss
  - » Non-uniform distribution of injected carriers

Interband Cascade (IC) Laser — Promising Approach

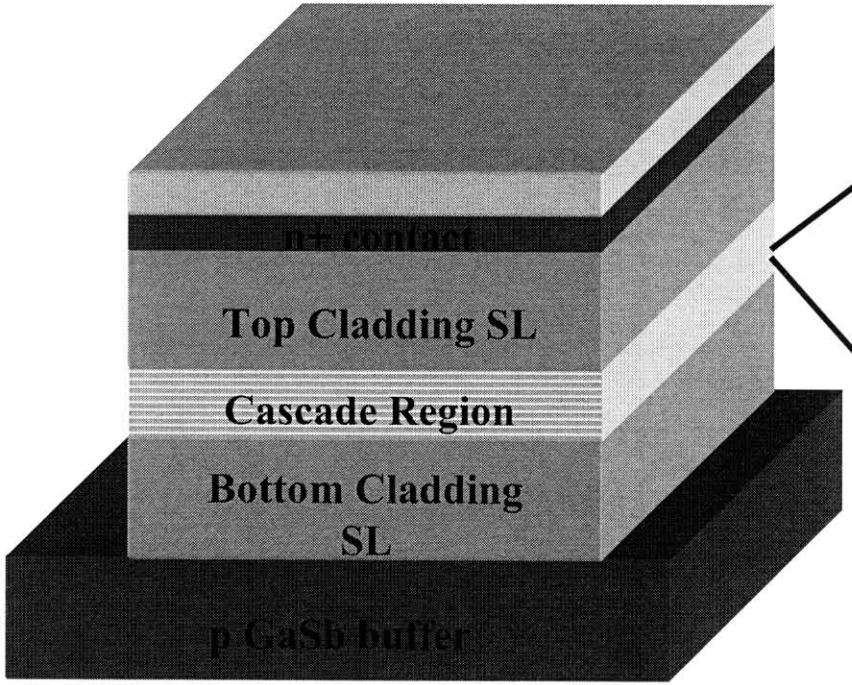
[original concept, R. Q. Yang, Superlattices and Microstructures, **17**, 77 (1995)]



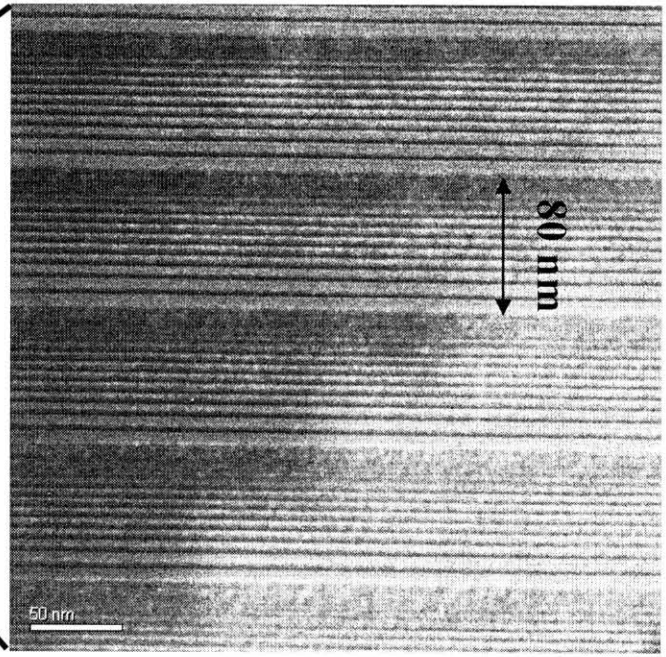
- **cascade process —**
  - »high efficiency, large output power, uniform injection over every stage, low carrier concentration, thus lower loss
- **interband transition —**
  - »circumvents fast phonon scattering
- **quantum engineering at sub-nanometer scale and Sb-based type-II QW system**
  - »suppresses non-radiative Auger losses
  - »allows for wide wavelength tailoring range
  - »excellent carrier confinement because of band-gap blocking feature

→ **Low threshold current, high efficiency, high output power mid-IR lasers**

Typical laser structure, MBE growth and fabrication



TEM image



Four Cascade Stages

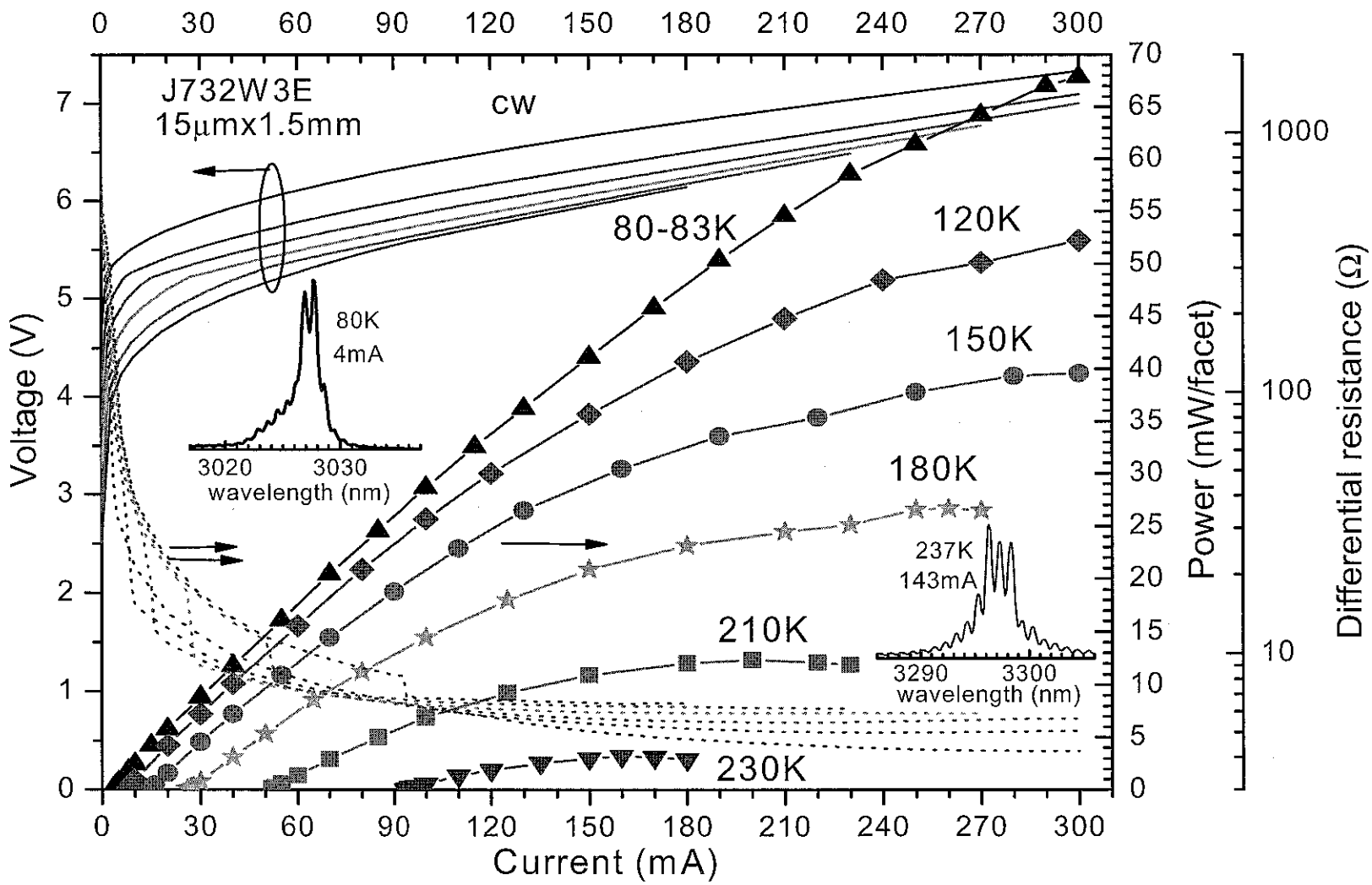
> Structure is usually grown on a GaSb substrate

> The whole structure is very complicated — more than 2000 epitaxial layers, some just a few atoms thick

> requiring sophisticated growth technology such as molecular-beam epitaxy (MBE) with precise controls

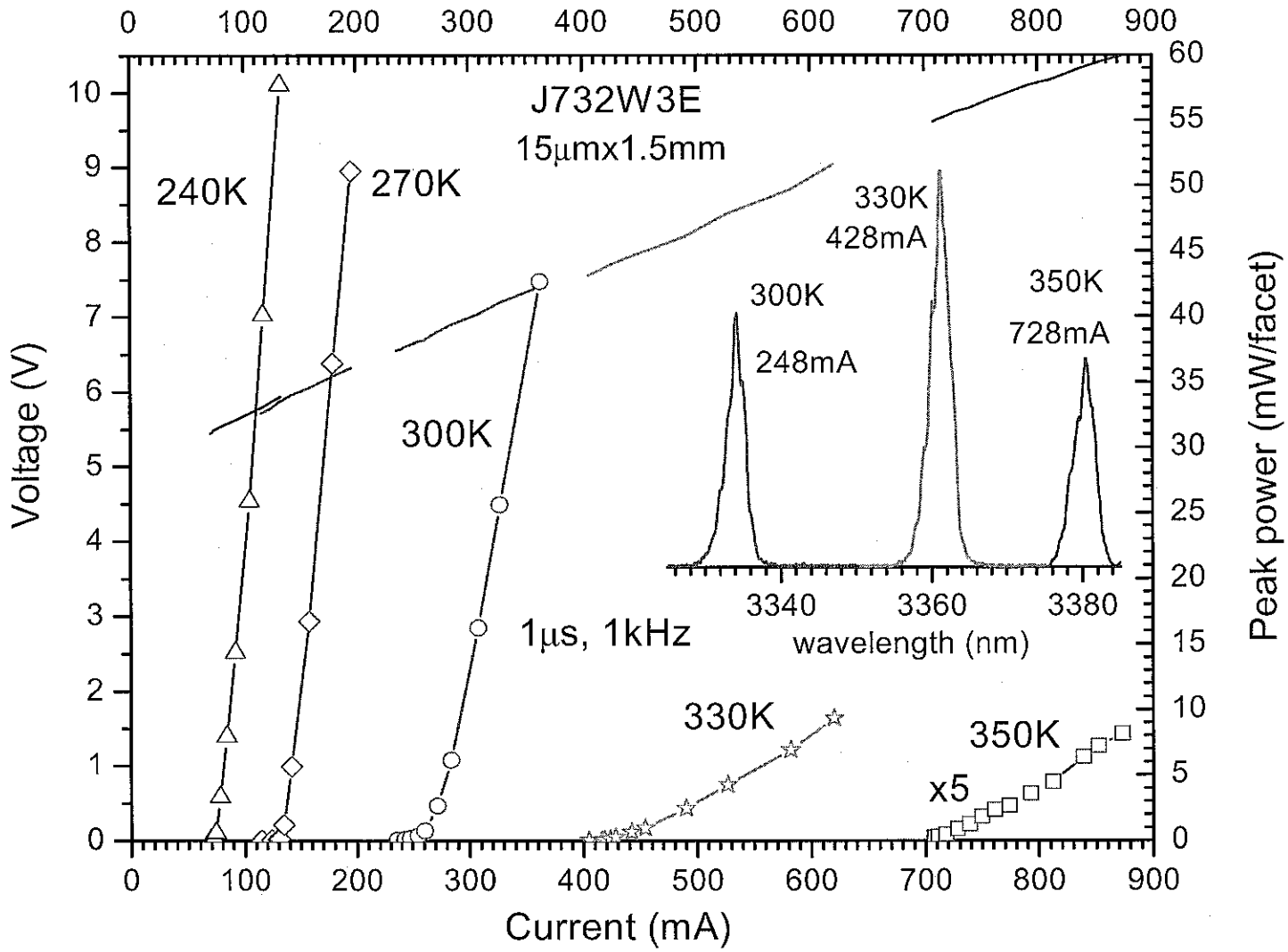
- Samples were typically processed into deeply-etched mesa stripe lasers
- Laser bars were cleaved to form cavities (0.5-1.5 mm) with both facets left uncoated
- Laser bars were affixed with indium or silver epoxy, epilayer side up, onto a copper heat sink.

cw operation of an IC laser



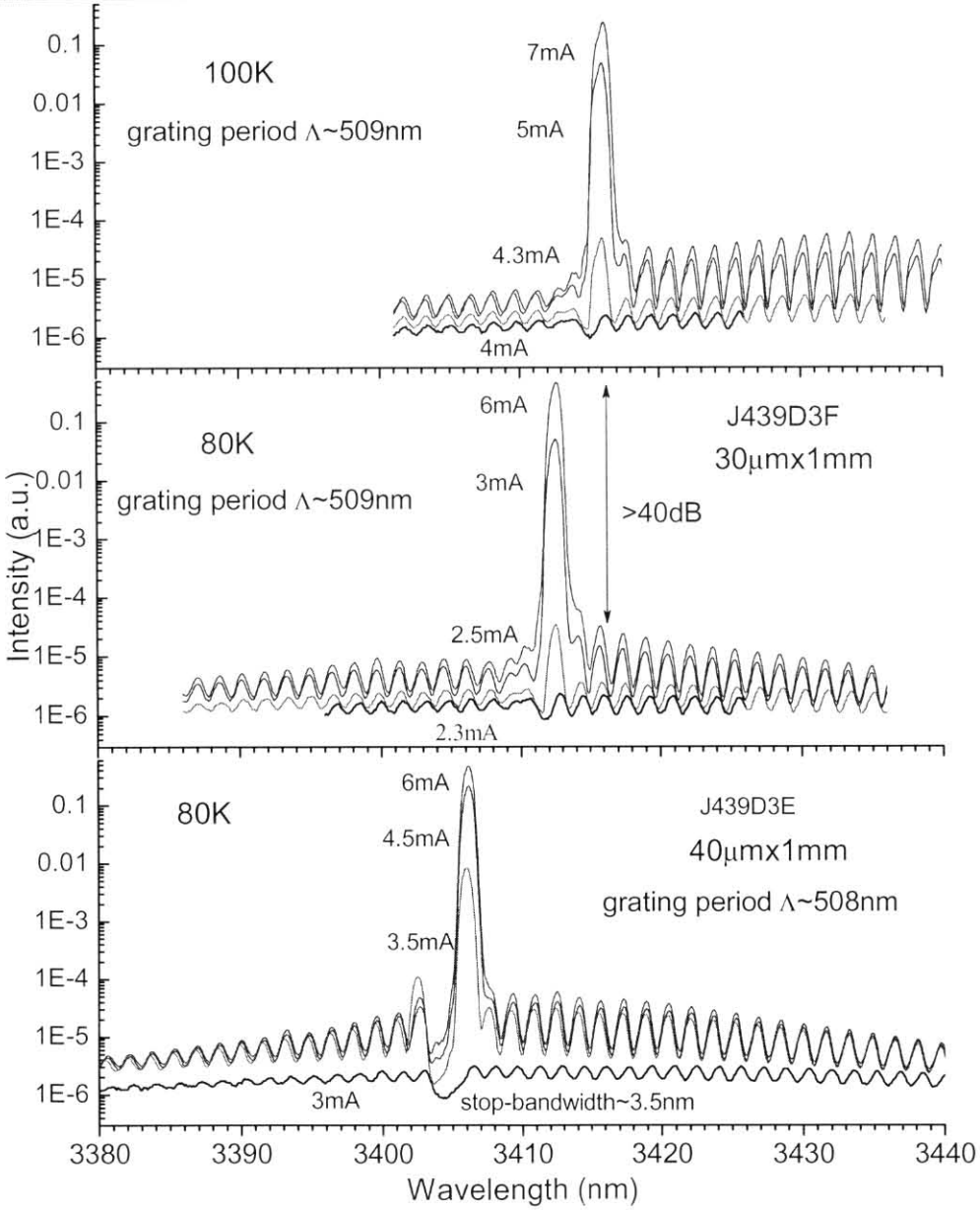
- Low power consumption (e.g., <20 mW at 80 K with I_{th} ~3.5 mA, V_{th}~5.3 V)
- cw operating temperature up to 237 K without special thermal dissipation enhancement

pulsed operation of the laser at high temperatures



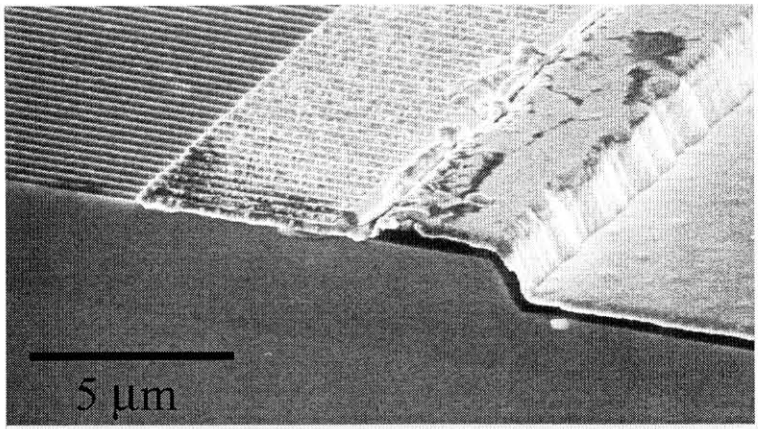
pulsed operation up to 350 K (limited by cryostat setting), highest ever-reported among mid-IR interband diode lasers

Single-mode DFB interband cascade lasers



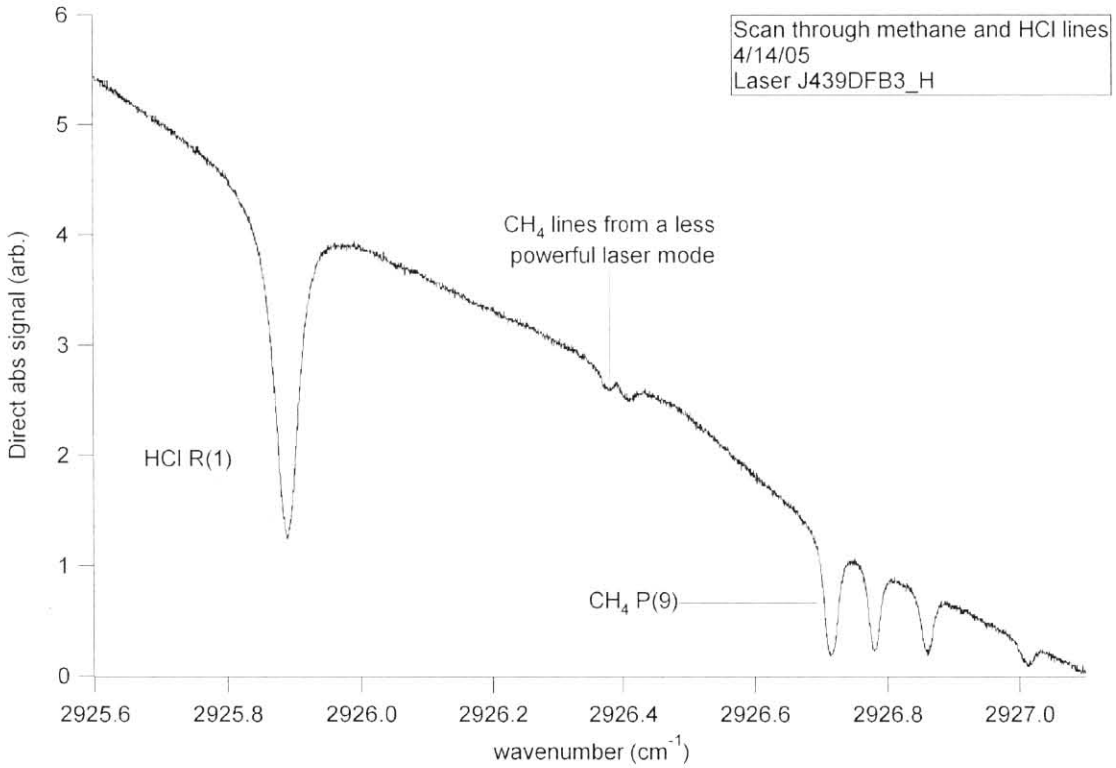
- Developed single-mode DFB interband cascade (IC) lasers near 3.4 μm with side-mode suppression ratio greater than 40 dB.
- Index-coupled DFB lasers

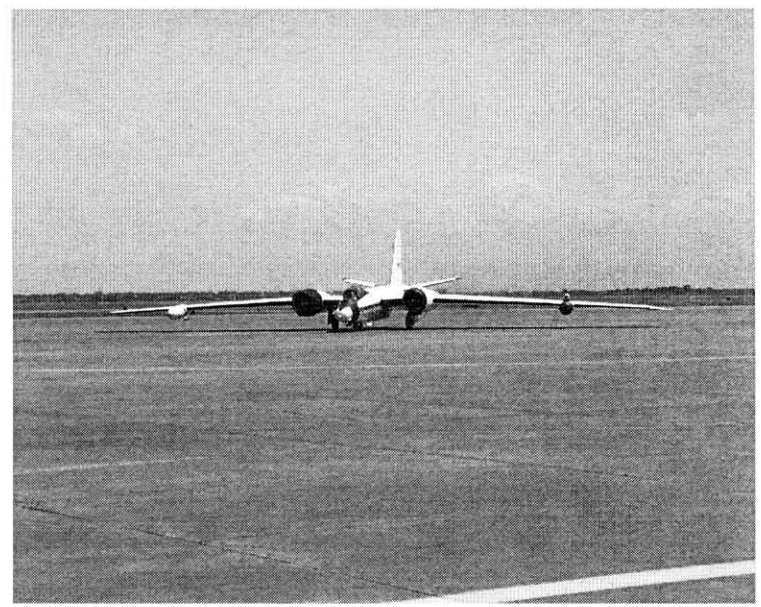
wavelength can be tuned by changing temperature and current



SEM image of a DFB laser. The grating was formed with e-beam writing and RIE etching into the top layer

Detection of CH_4 and HCl using a DFB IC laser



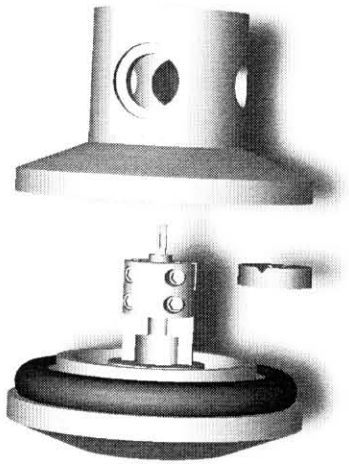


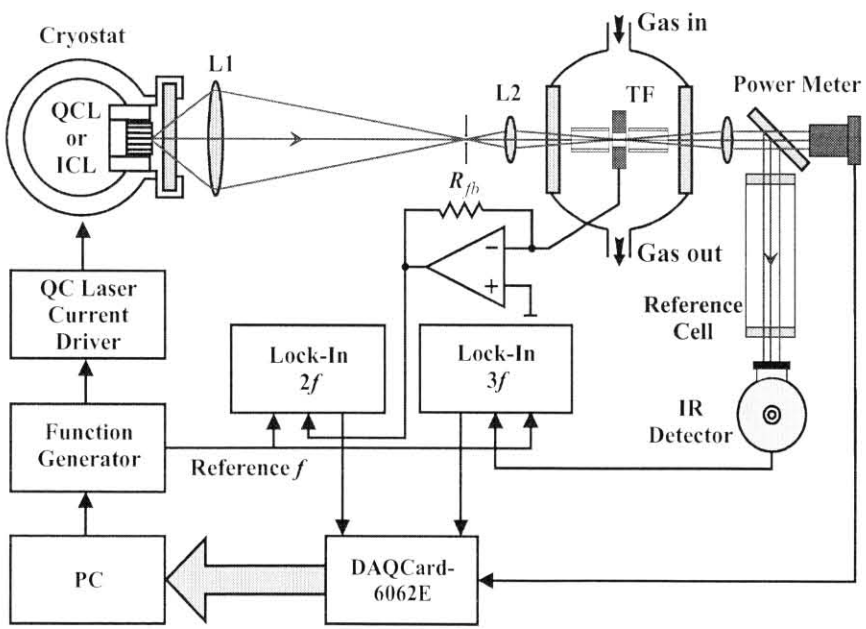
A DFB IC laser was integrated into Aircraft Laser Infrared Absorption Spectrometer, which was flown in WB57F aircraft and measured atmospheric CH4 profile in 2005

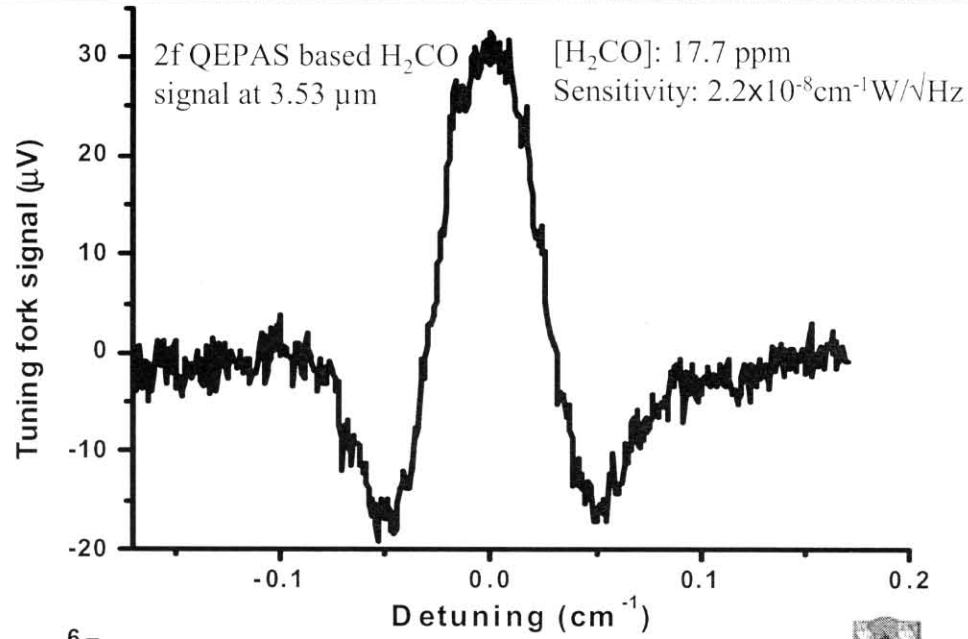
Detection of formaldehyde (H_2CO) using DFB IC lasers

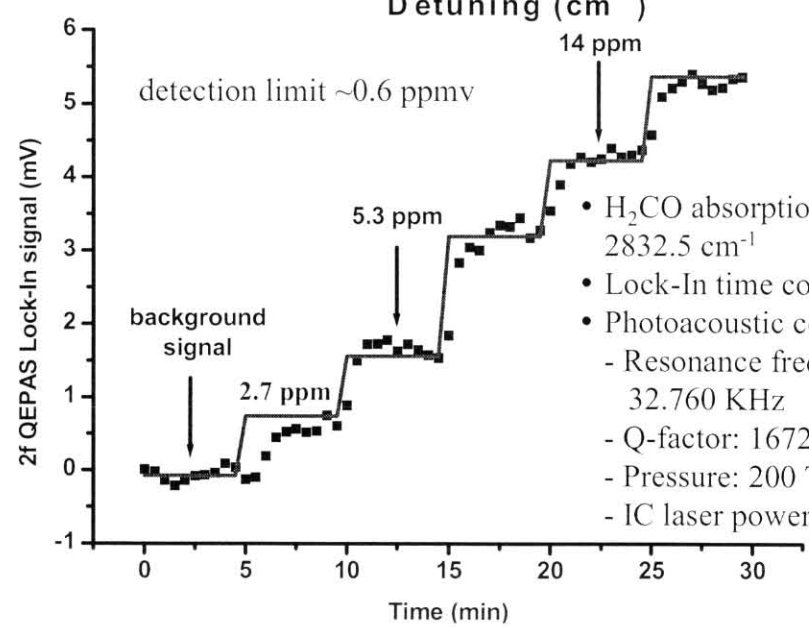
[M. Horstjann, *et al. Applied Physics B* **79**, 799 (2004)]

Cascade laser based Quartz-Enhanced Photoacoustic Spectrometer



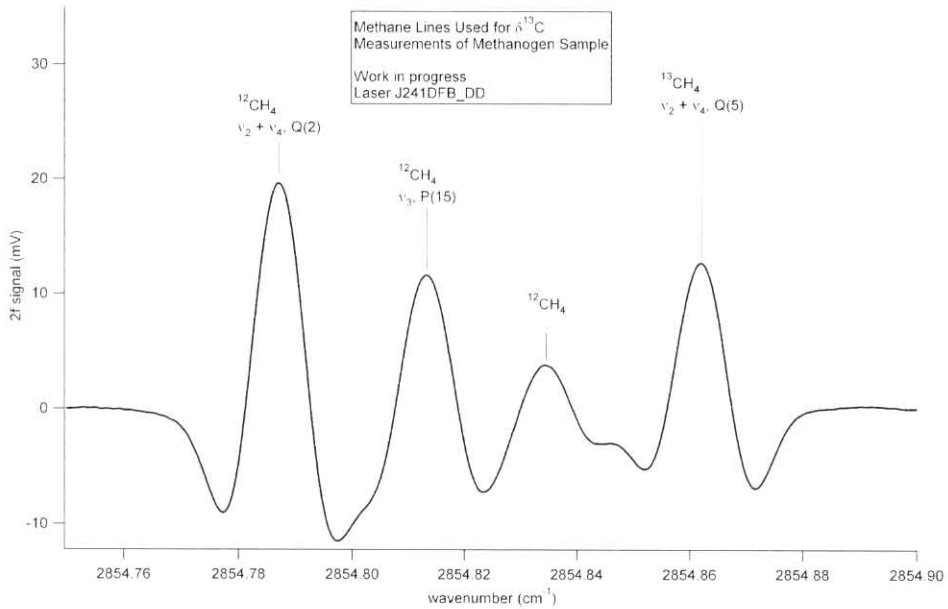


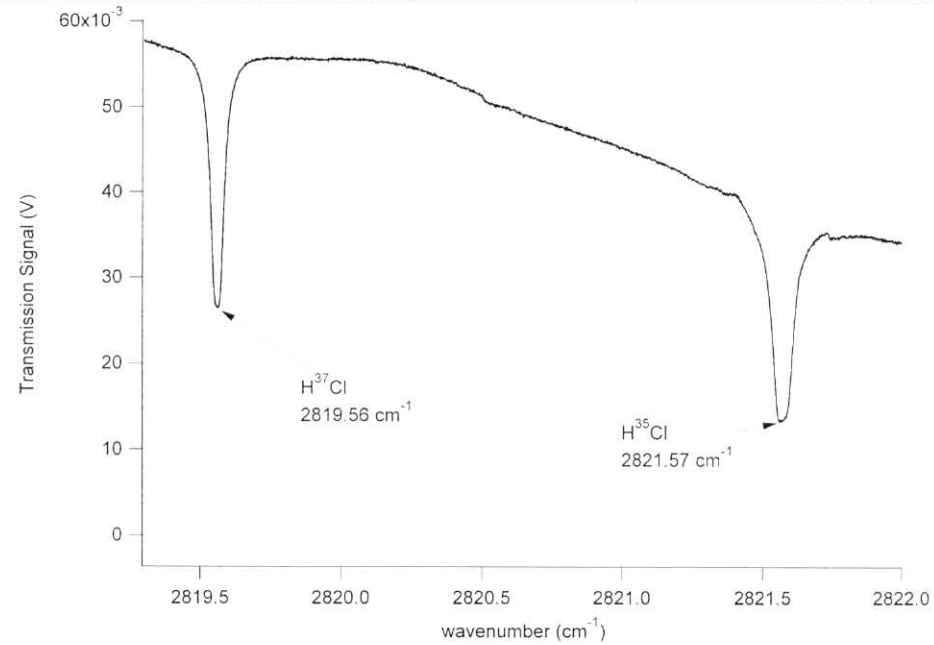




- H_2CO absorption frequency: 2832.5 cm^{-1}
- Lock-In time constant: 10s
- Photoacoustic cell:
  - Resonance frequency: 32.760 KHz
  - Q-factor: 16725
  - Pressure: 200 Torr
  - IC laser power: 6 mW

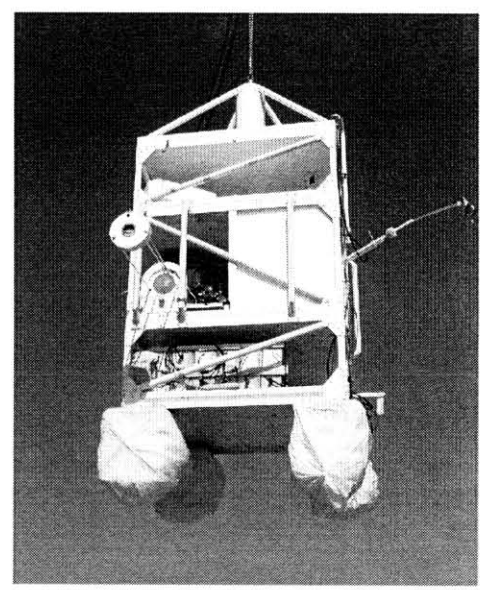
Detection of CH_4 and HCl using IC lasers near 3.5 μm



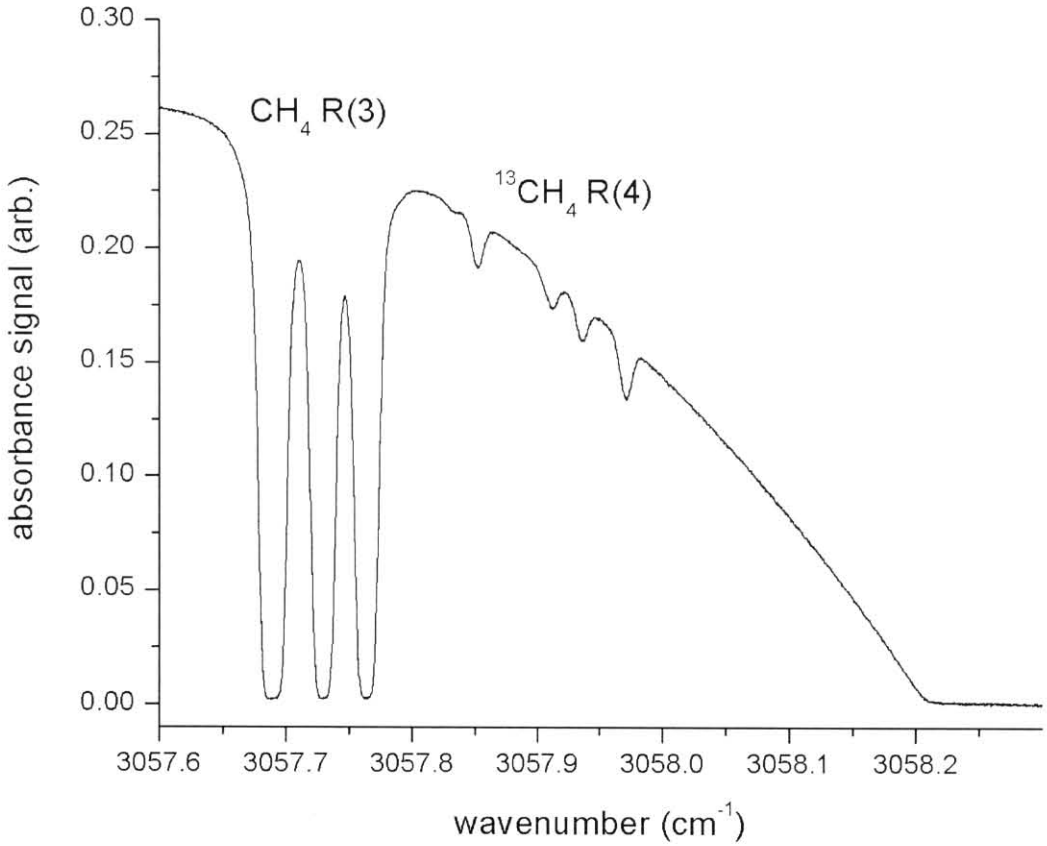


Measured methane isotope ratios ($^{13}CH4/^{12}CH4$) to better than 5 per mil

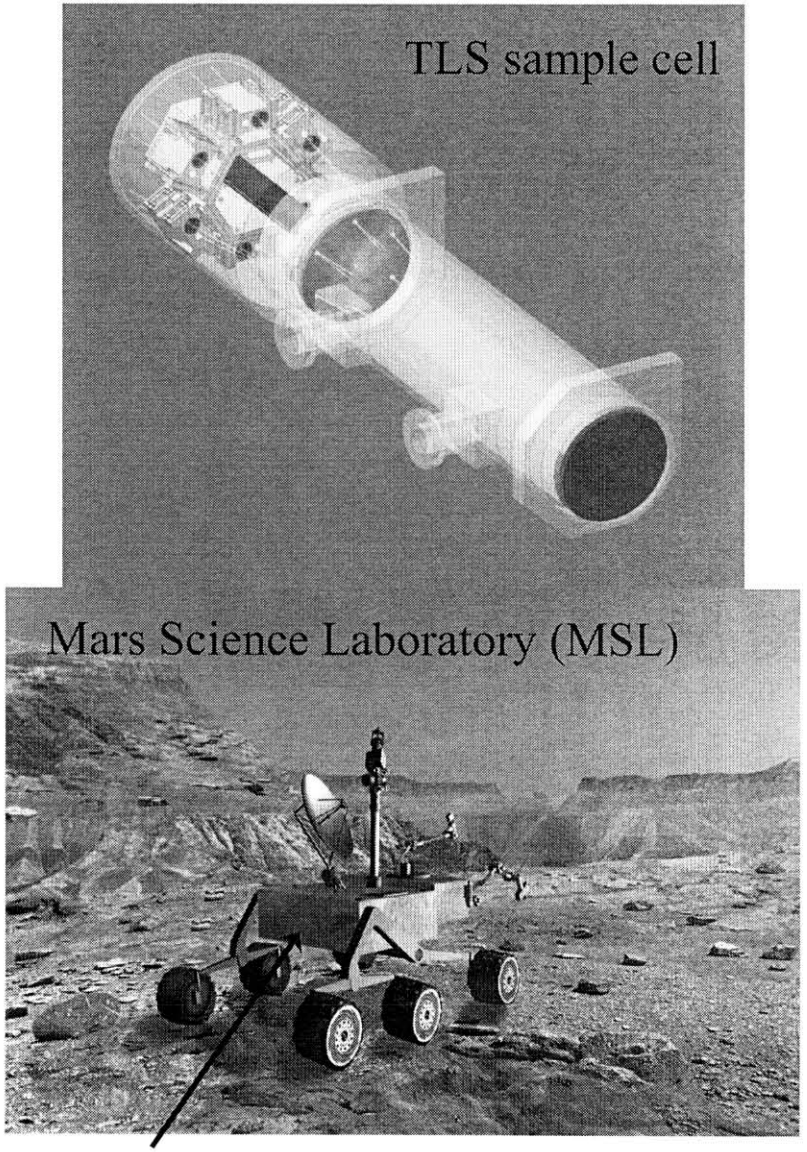
The laser was installed into a high-altitude balloon instrument (ALIAS-II) launched on Sept. 19, 2004 out of Ft. Sumner, NM and flew to 104,000 ft. The laser worked well in measuring HCl profile in the stratosphere.



DFB IC Laser for 3.27 μm Channel in TLS/MSL

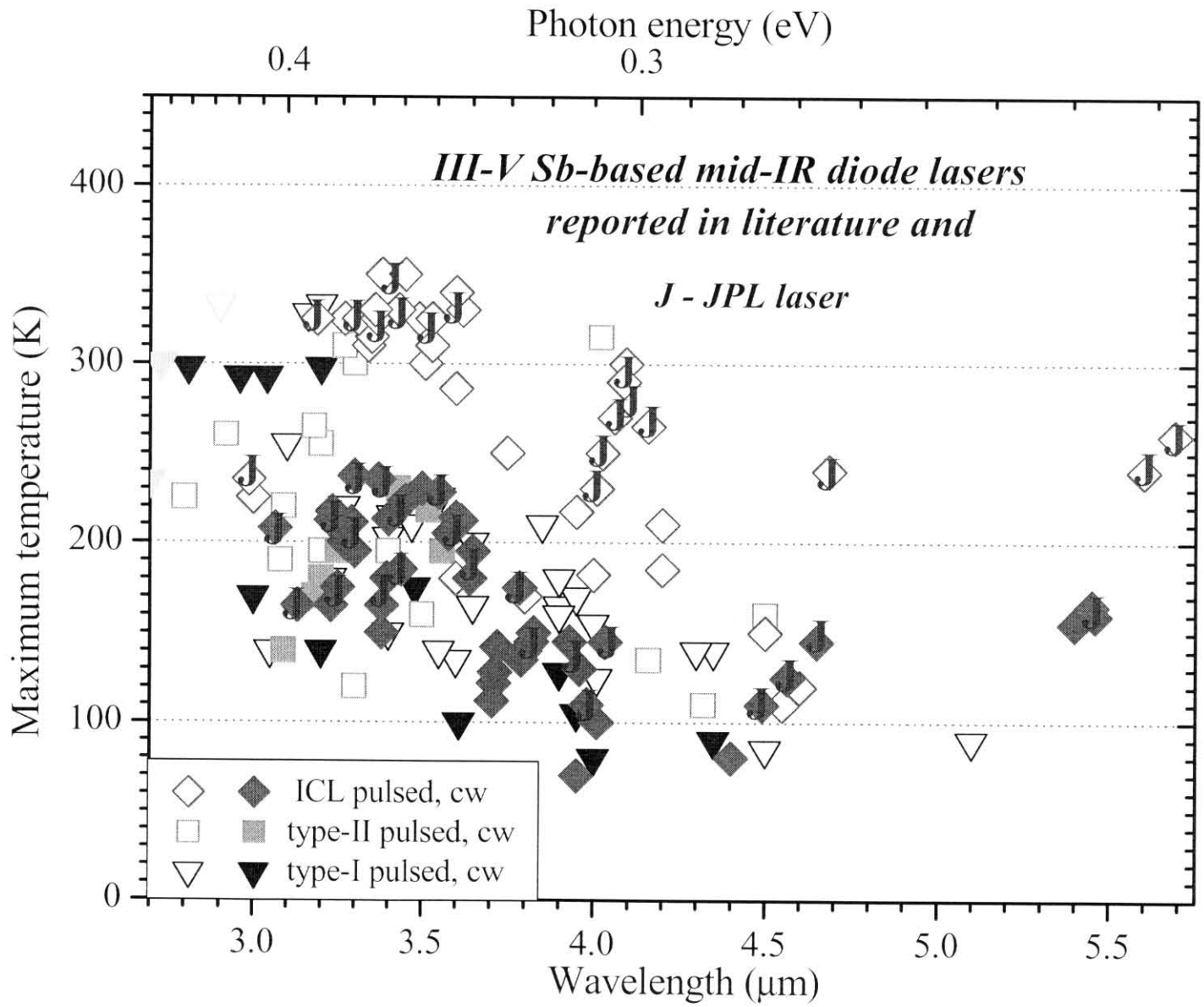


single-mode DFB lasers around 3.27 μm with nearly 100% mode purity. The lasing wavelength is one wavelength channel selected for the CH4 and isotope ratio measurement by the Tunable Laser Spectrometer (TLS) on the Mars Science Laboratory (MSL) 2009 mission.



JPL Tunable Laser Spectrometer

Where are we?


Photon energy (eV)
0.4
0.3
III-V Sb-based mid-IR diode lasers
reported in literature and
J - JPL laser
Maximum temperature (K)
400
300
200
100
0
3.0
3.5
4.0
4.5
5.0
5.5
Wavelength (μm)
ICL pulsed, cw
type-II pulsed, cw
type-I pulsed, cw

Summary

- Significant progress has been made
  - above room temperature (up to 350K) pulsed operation has been demonstrated
  - cw operation temperature has been raised up to 237 K
  - DFB IC lasers have been applied for the detection of trace gases such as CH_4, HCl, and H_2CO
  - Devices have been operated continuously over several hundred hours without degradation
- Main challenge remains for many potential applications of ICLs
  - cw operation at room temperature and above with significant output powers
- There is still significant room for improvement
  - laser design and material quality – many parameters have not been optimized
  - device fabrication and thermal management (passivation, better mounting, etc.)
  - Significantly higher output power can be achieved with laser arrays

Thank You

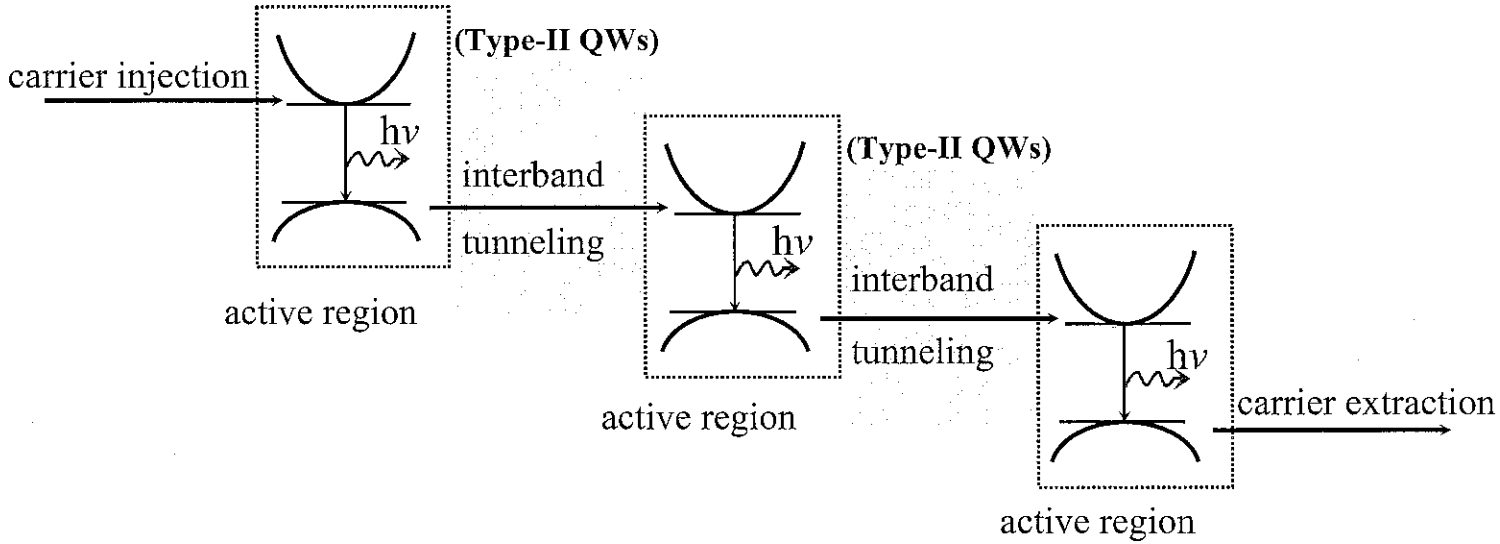
Back-up

Motivations

- Applications (must be useful)
- Curiosity and interest (should have fun!)
- Fundamental or/and technology challenges (excitement)

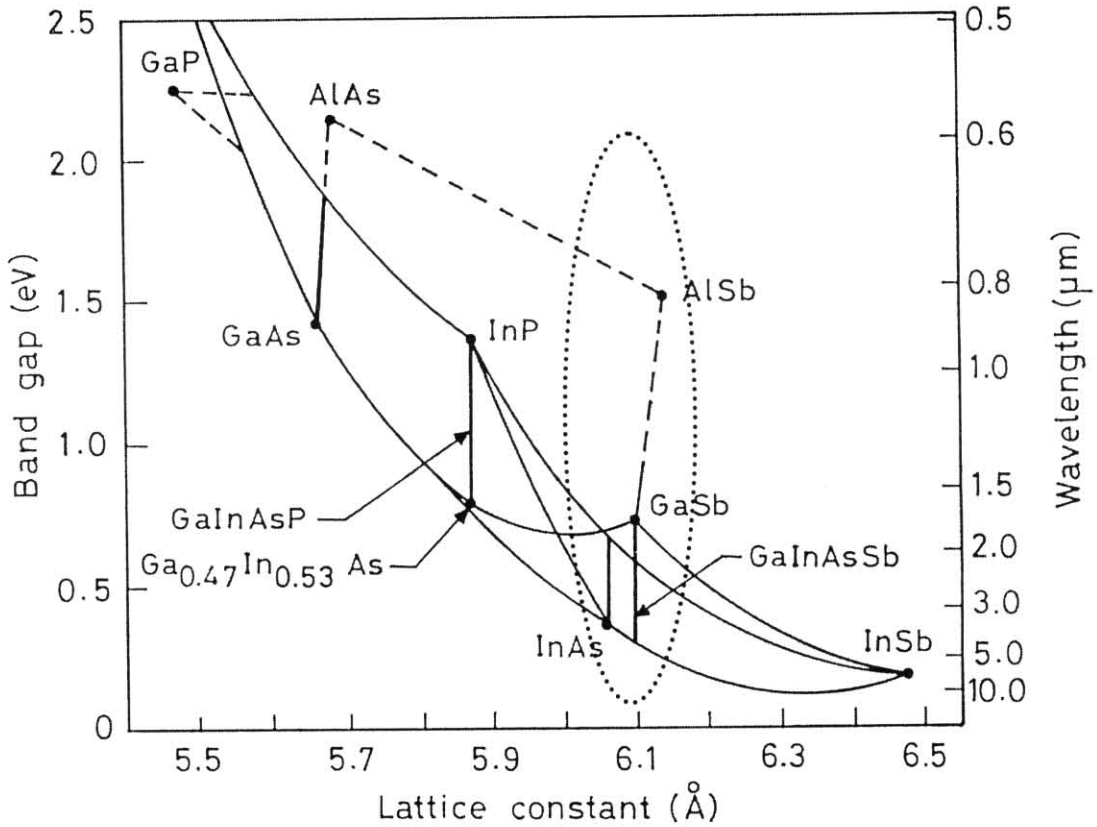
What is Interband Cascade (IC) Laser?

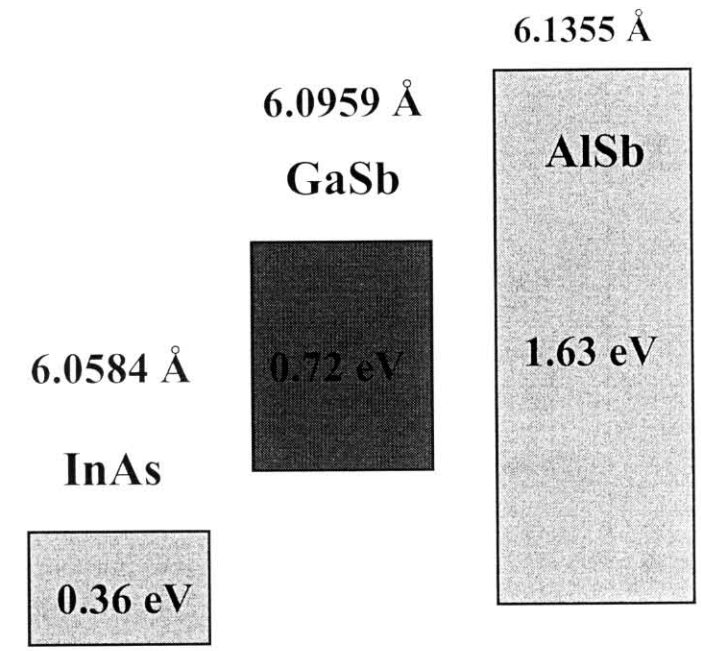
[original concept, R. Q. Yang, Superlattices and Microstructures, **17**, 77 (1995)]



- **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

6.1 Angstrom Materials





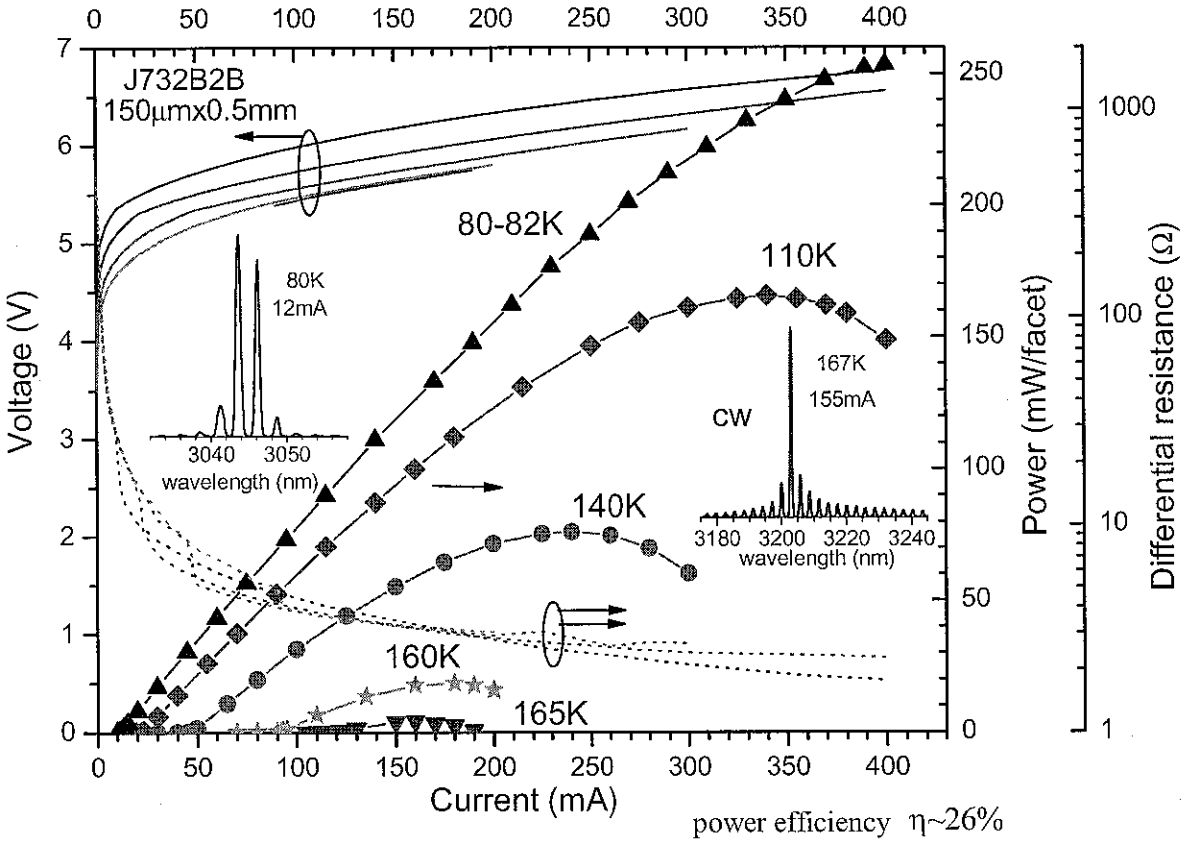
Type-II band gaps & alignments

- Nearly lattice-matched system
- Unusual band-edge alignments (type-I, type-II staggered, type-II broken-gap) most versatile heterostructure system
- Very low contact resistance between *n*-type InAs and metals

Review of IC Laser Development

1994	The concept of ICL was first proposed by Yang (Univ. of Toronto, Canada)
1995/96	Refined design, calculations suggested the feasibility of cw operation at room temperature with high output powers (Meyer, Vurgaftman, Yang, Ram-Mohan)
1996	Mid-IR electroluminescence and Stark effect (blue shift) observed in IC emitters (with collaborative efforts between UH, QET, NRC Canada, Sandia, Bell Labs)
1997	ICL was first demonstrated at a wavelength of ~3.8 μm by UH/Sandia 4-μm ICLs, DQE >200%, near quasi-cw operation (UH/QET) 3.5-μm ICLs with "W" active regions, pulsed operation up to 286 K (NRL/UH)
1999	Mid-IR ICLs demonstrated at ARL (2nd in successful MBE growth of ICLs) with DQE >600%, peak power ~ 6 W/facet, peak power efficiency ~10%, cw operation
2000	Low J_{th} (~44 A/cm^2), record-high power efficiency (>14% in cw >18% in pulsed)
2001	pulsed operation of an IC laser up to 300K at 3.5 μm, DFB IC laser demonstrated
2002	IC lasers demonstrated at JPL (3rd in successful MBE growth of ICLs)
2003	Above-room-temperature operation (up to 325 K) achieved in pulsed mode, very low J_{th} (~8-9 A/cm^2 at 80 K), cw operation crossed 200 K, single-mode DFB lasers have been explored in experiments for sensing application.
2004	Single-mode cw DFB IC laser was used in high-altitude balloon instrument for successfully measuring HCl profile in the stratosphere; extended lasing wavelength into 5.2-5.6 μm region with cw operation up to 165 K.
2005	Threshold current density lowered at RT, cw power >1 W at 77K

A broad-area laser with a short cavity



- Output P~253mW/facet at 82 K and at 400 mA.
- J_{th}~15A/cm^2 at 80 K
- **Wall-plug η as high as 26%**
- Pulsed operation up to 320K with J_{th}~1 kA/cm^2 at 300K;

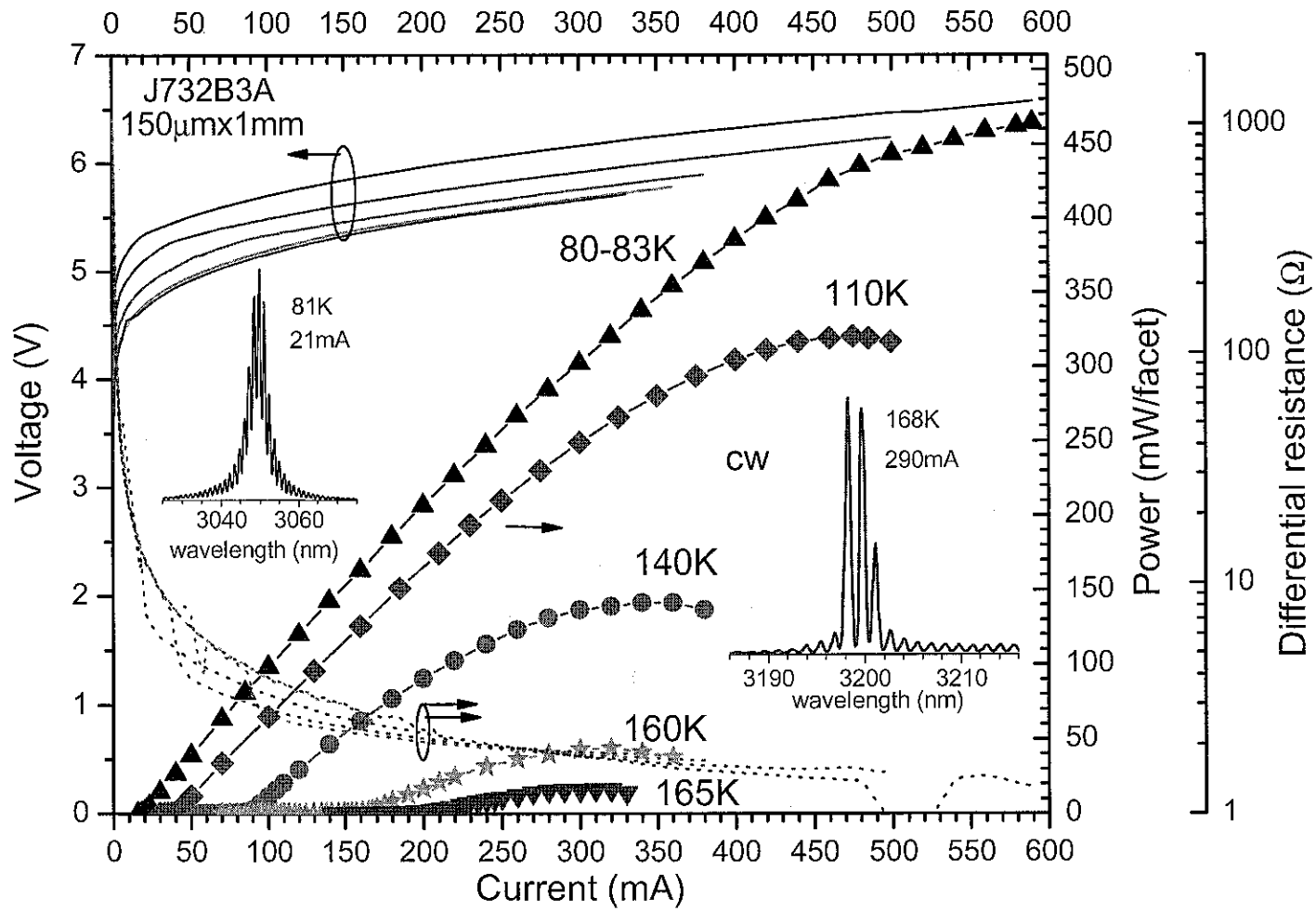
R_{sth} ~ 37.5 K·cm^2/kW at ~167K (specific thermal resistance) – bonding is not very good

cw operation to ~167K was limited by substantial heating for broad-area lasers

Output power P can be higher with facet coating, and/or better thermal management

High power interband cascade laser with facet coating

HR (~78%)
AR (~5%)

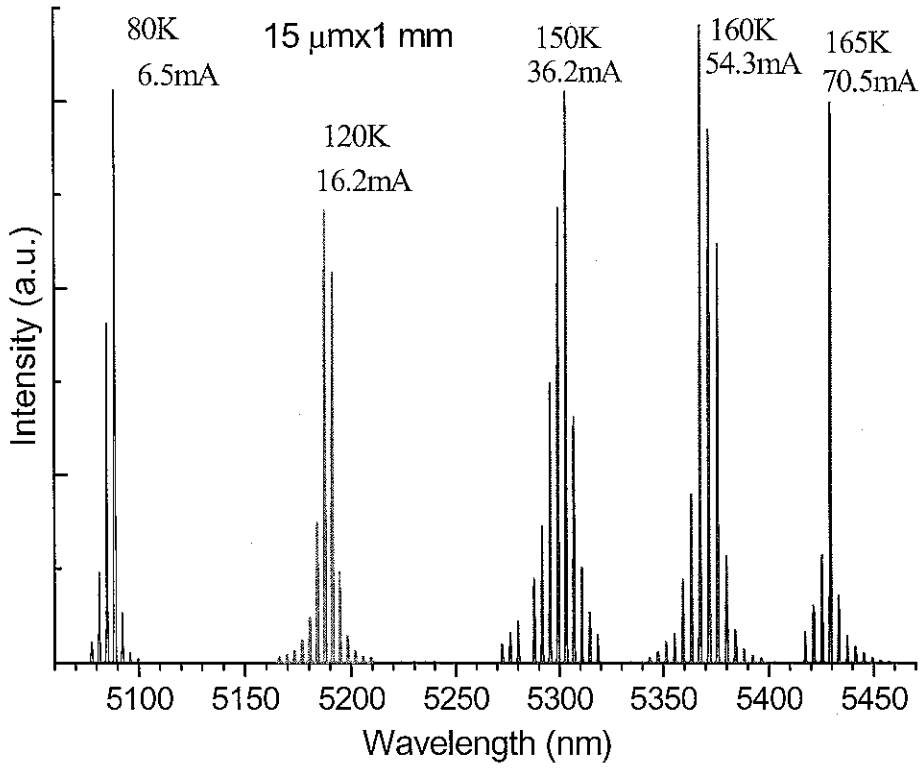


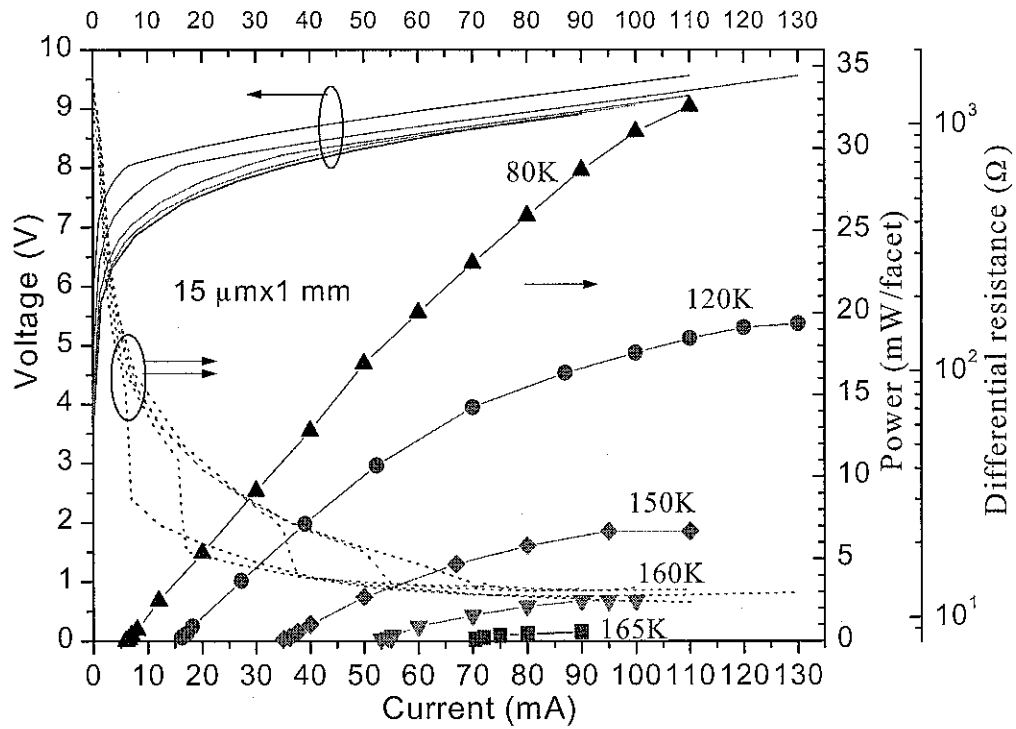
More than 460mW cw output power from one facet of an IC laser at 600 mA

NRL recently obtained output power of ~514 mW/facet from a uncoated IC lasers at 78K

A laser in the longer wavelength region

cw spectra of a 30-stage IC laser

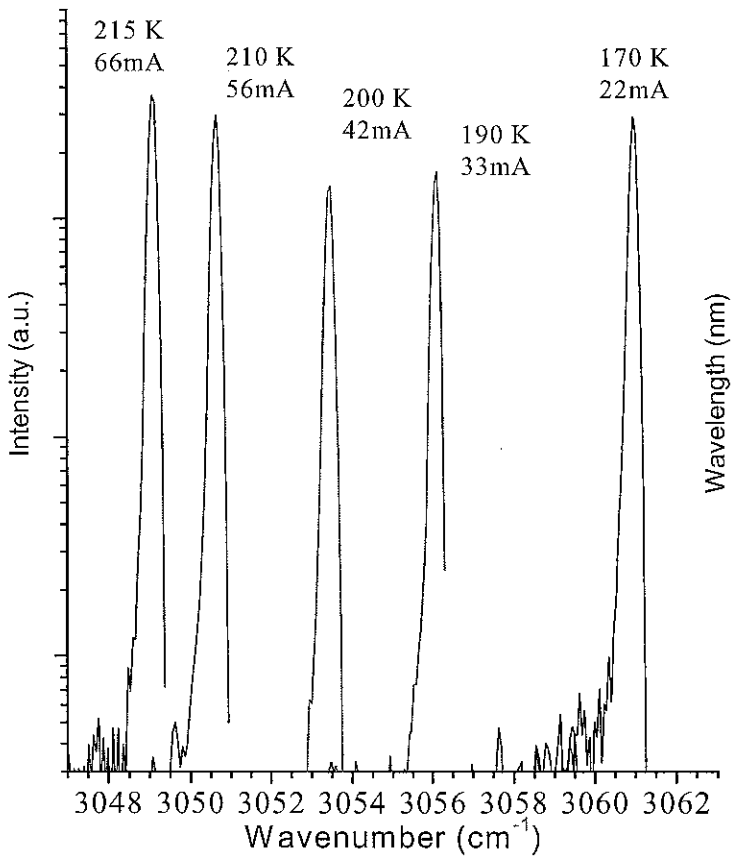


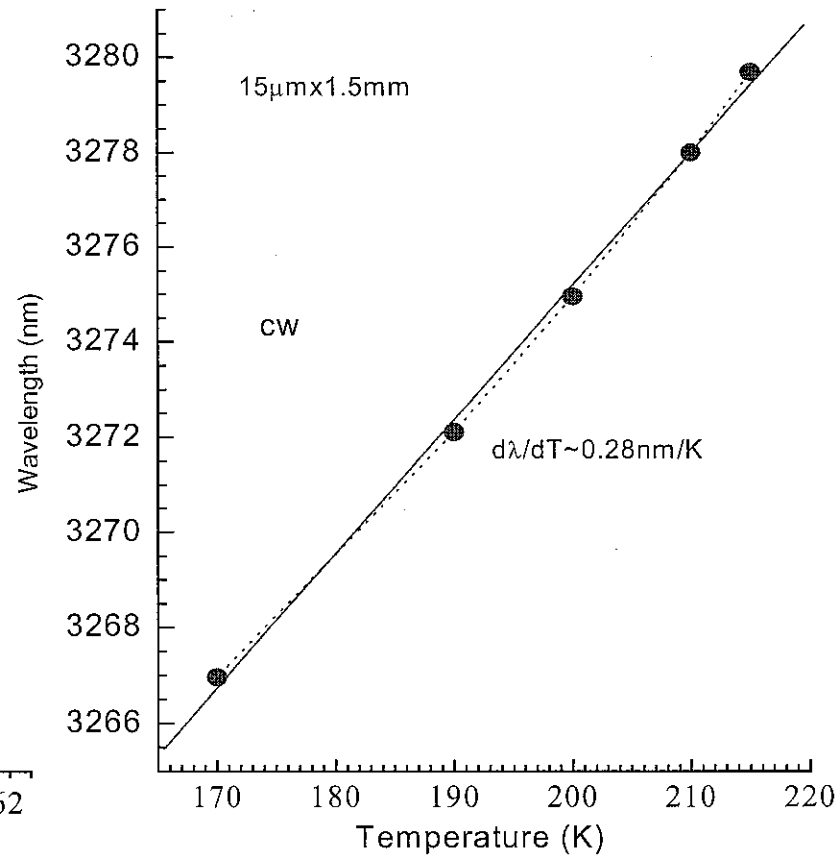


I-V-L characteristics in cw mode

Pulsed operation up to 260K

DFB IC laser at higher temperatures



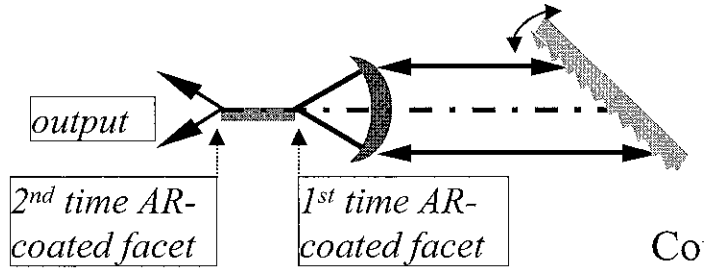
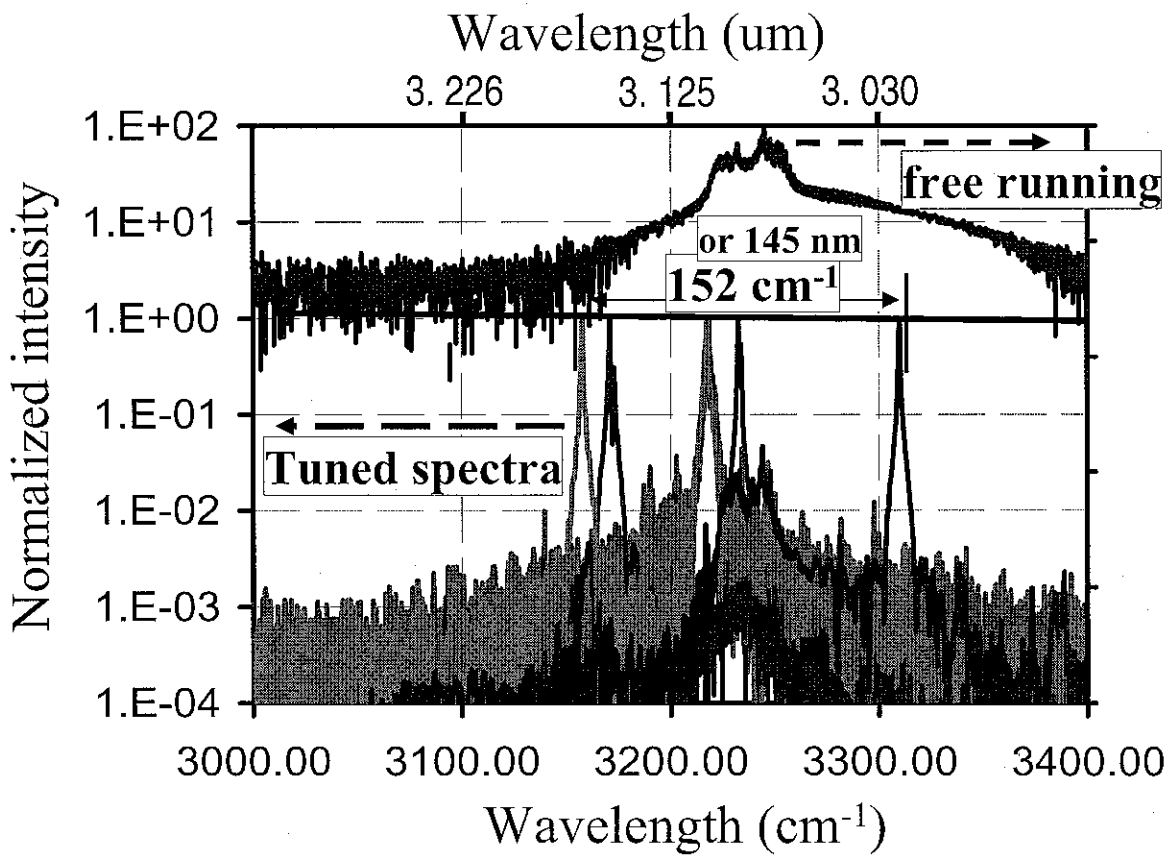


DFB laser can be operated in cw mode over 230 K with stable single-mode up to 215K

Febry-Perot lasers lased at temperatures up to 235K near 3.38 μm and 350 K near 3.45 μm in cw and pulsed modes, respectively

Performance in external cavity configuration

- Top spectrum is the free running spectrum of the laser. The estimate gain bandwidth is ~150 nm.
- Bottom part is the tuned spectra of the device. The lasing spectra are nearly single mode with FTIR resolution: 0.125 cm^{-1}. Tuning range is ~145 nm at highest power condition with CW output power >10 mW from the 2nd time AR-coated facet.
- The power dropped to its half at both ends of the tuning range.



Courtesy of Prof. Han Le