Low power consumption lasers for next generation miniature optical spectrometers for major constituent and trace gas analysis

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Outline

- Introduction
- Laser Spectroscopy and status of laser based spectrometers
- Semiconductor lasers for spectroscopy
  - (types, availabilities, and performane limitations)
- Performance of lasers developed at JPL
  - 1.2-2.1 micron for H20, CO2
  - 3.0-3.7 micron for detection of HCl, HF, HCN
  - 4.6 micron for detecting CO and CO2
- Gas sensor development by Fraunhofer Institute
- Summary

Introduction

- **The air quality of manned spacecraft needs to be continuously monitored to maintain an acceptable quality**

- **Several types of instruments are used and new instruments are evaluated for continuous air quality monitoring:**
    - Volatile Organic Analyzer
    - Analyzing Interferometer for Ambient Air (ANITA)
    - Electronic Nose
    - Vehicle Cabin Air Monitoring (VCAM)
    - **Tunable Laser Spectrometers (TLS) via Laser spectroscopy**
- **TLS can provide substantial improvement over the current state of the art instruments for monitoring of major constituents and post fire contaminants**

Laser spectroscopy

Viable Candidate for Air Monitoring

How it works?

Gases of interest for environmental monitoring have absorption band in the near to mid infrared range

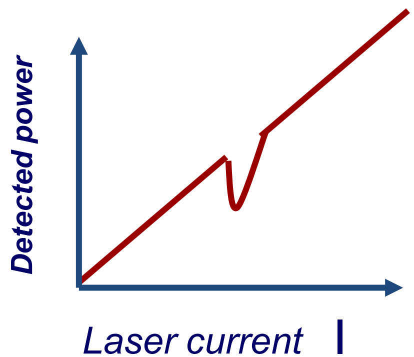
Important features

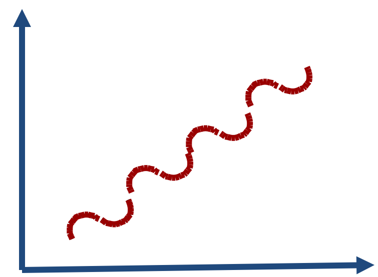
- High sensitivity
- High selectivity
- Non-intrusive
- Good for remote sensing

Absorption spectroscopy is currently the foremost technique for quantitative assessments of atoms and molecules in gases

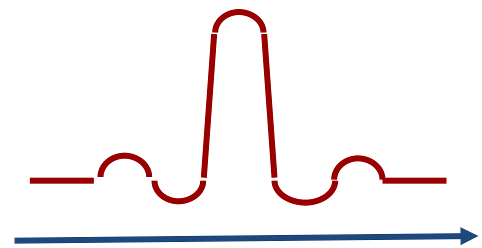
Laser spectroscopy

- **Direct absorption spectroscopy**
  - Provides absolute quantitative assessment of species
  - Relies on small change in power of the laser *(limited detectability 10^{-3} range)*
- **Modulated techniques**
  - Wavelength or Frequency modulation spectroscopy *(detectability in the 10^{-5} range)*





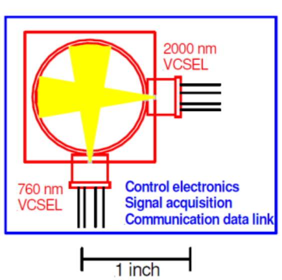
Current Scan waveform



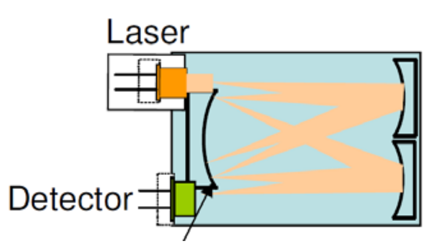
Second harmonic signal

- **Cavity enhancement**
  - Provide 2-5 orders of magnitude enhancement

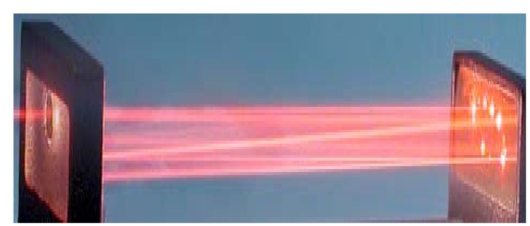
IS-Vista photonics



White Cell- Fraunhofer



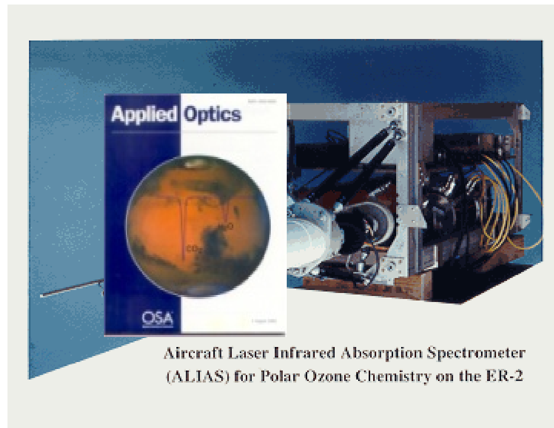
Herriott Cell- JPL



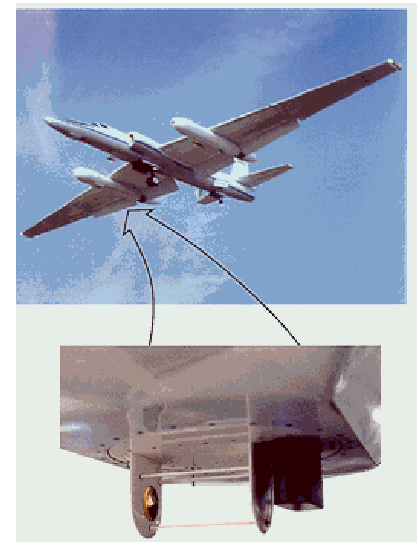
Laser spectrometers
as science Instrument

Balloon-borne Laser In-Situ Sensor (BLISS) 1983-1992

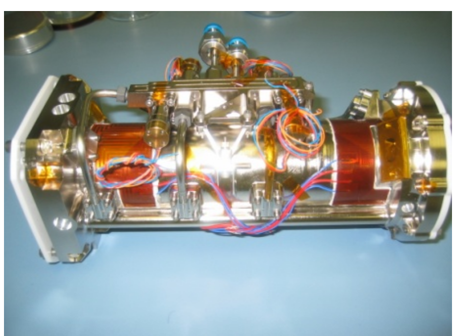
Aircraft Laser Infrared Absorption Spectrometer (ALIAS)



JPL Near-IR Laser Hygrometer for the ER-2, and WB57F Aircraft

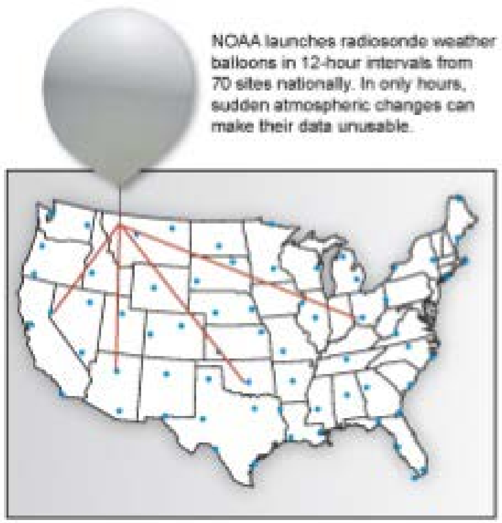


Tunable Laser spectrometer on MSL
JPL 3.27 μm Laser

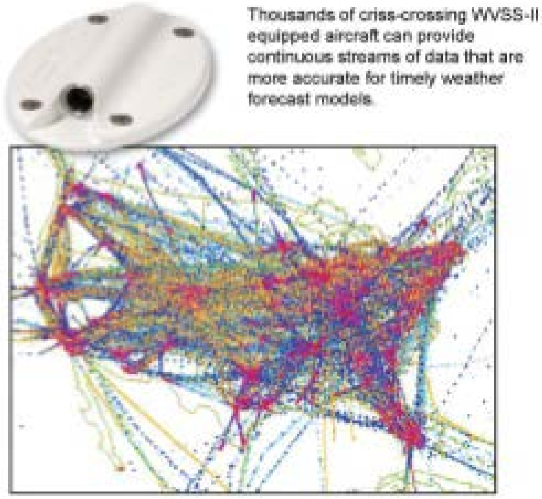


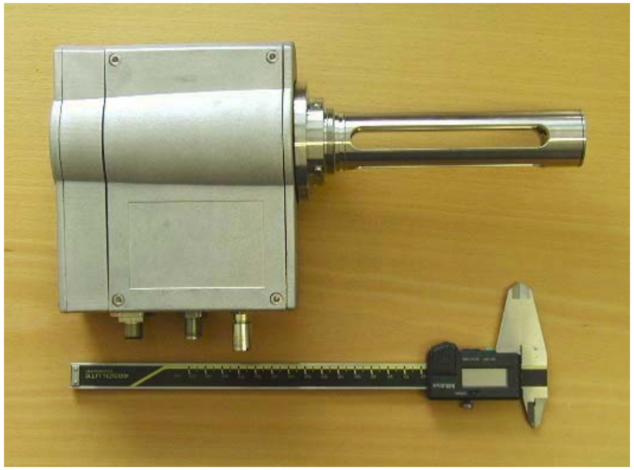
(2011 launch)

Commercially available laser spectrometers



Spectra-sensors Water Vapor Sensor System (WVSS-II)





Vaisala's oxygen transmitter, consisting of the spectrometer probe and associated electronics.

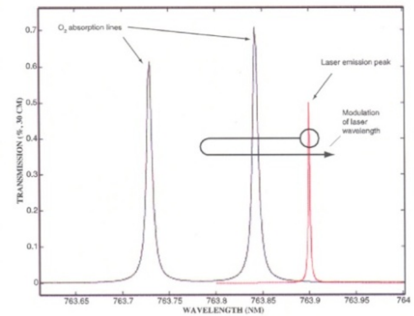
Few manufacturers:
- PKL technologies
- Siemens
- Amatek

Lasers requirements & types

for spectroscopy

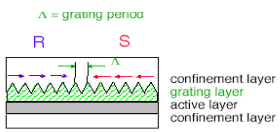
Requirements

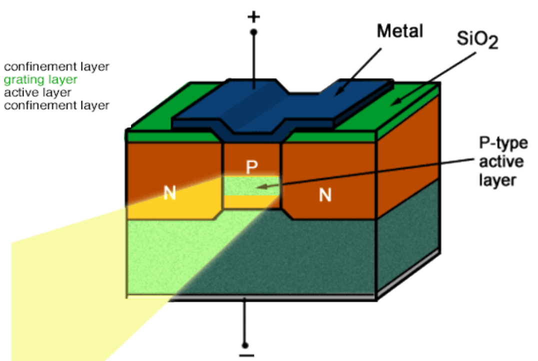
- Wavelength coincide with the absorption of the gas of interest
- Narrow spectrum
- Wavelength tunable
- Low drive power
- Room temp. operation
- Reliable

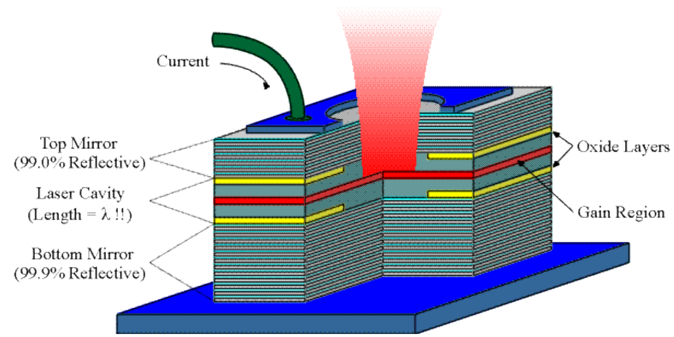


O_2 absorption spectrum

Edge emitters vs. VCSELs

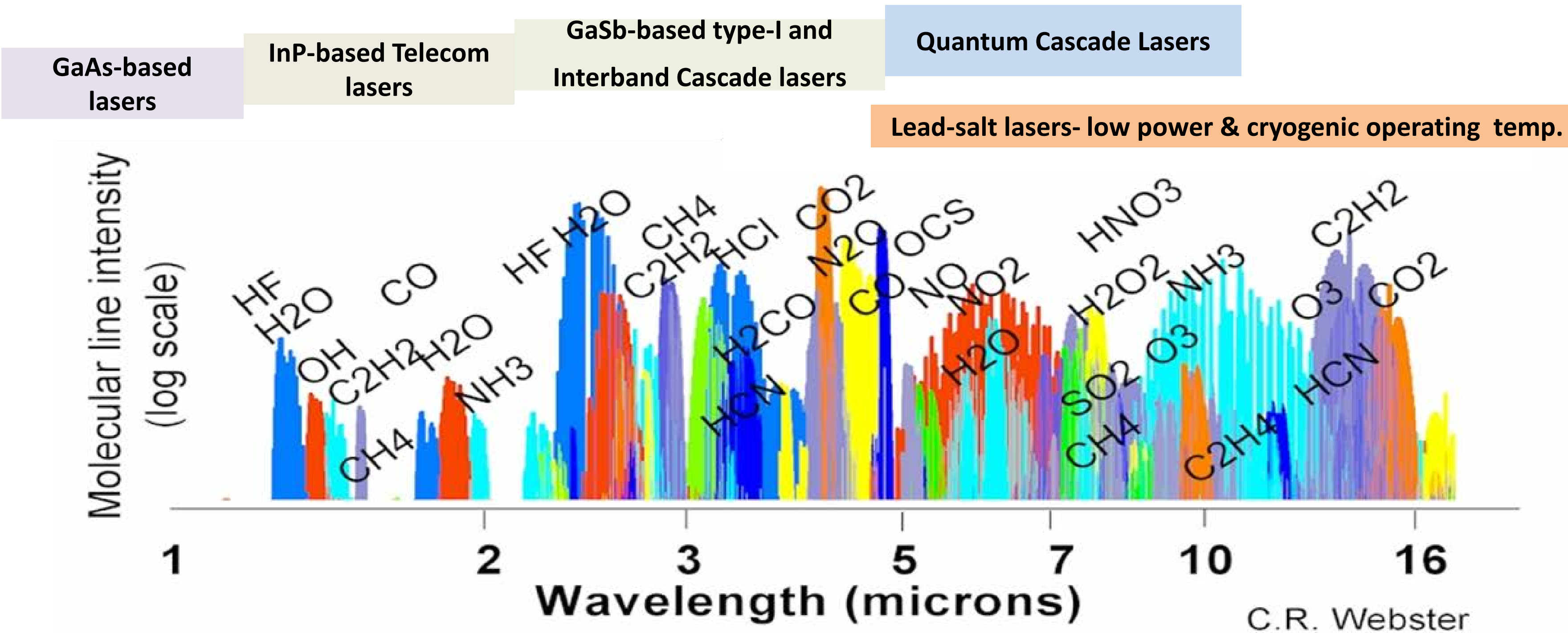






	Edge-Emitter	VCSEL
input electrical power	200-300 mW	10-20 mW
output power	10-100 mW	1-5 mW
λ	Available up to 2.8 μm	Available up to 2.3 μm
technological readiness	Requires distributed feedback	Inherently single freq.
Beam quality	Elliptical (undesirable)	circular
	Suitable for all techniques	Not suitable for PA spectroscopy

Laser Diode Operating Ranges



- No single laser can cover the entire wavelength of interest
- Not all laser types perform the same nor have the same reliability and life expectancy
- **Variety of material systems, designs, and fabrication techniques need to be developed for diode lasers to cover the wavelengths of interest**

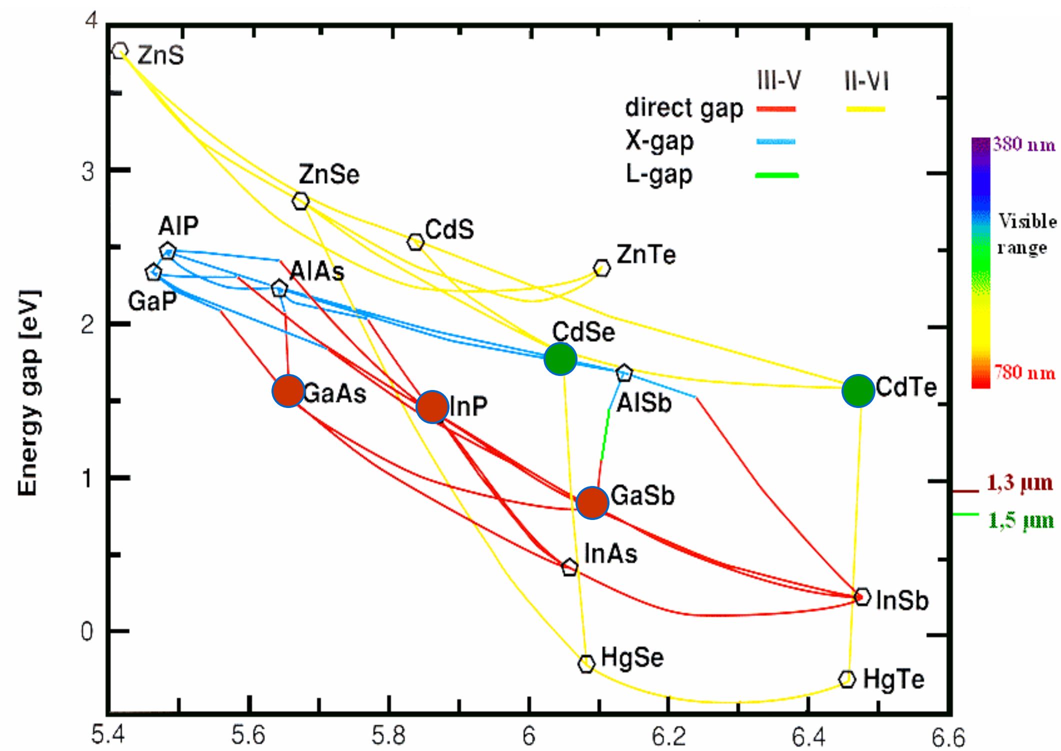
Laser material for specific wavelength

Choice of substrates

III-V → GaAS, InP, GaSb

II-VI → CdTe, CdSe

- ***Material composition***
  - ***III-V***
    - ***AlGaAs/GaAs*** ***λ=0.78-0.9 μm***
    - ***InGaAsP/InGaAs*** ***λ=1.2-1.67 μm***
    - ***InGaAsSb/GaSb*** ***λ= 1.9-? μm***
  - ***II-VI***
    - ***Lead-salt*** ***λ= 3-15 μm***
      - ***low temp. operation***
      - ***Unreliable***

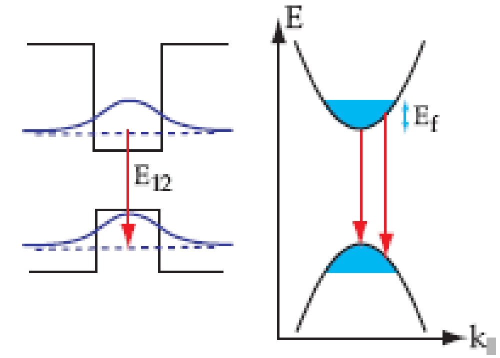


Alternative:
Bandgap engineering of III-V compounds on III-V substrates

Lattice constant vs. energy bandgap III-V and II-VI binary materials

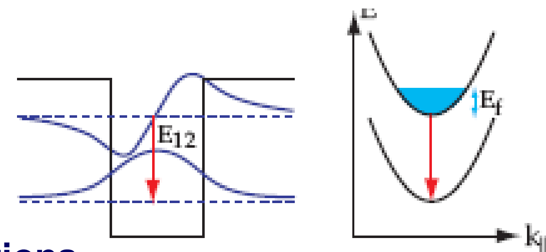
Bandgap engineering of the laser

Band to band transition
- Emit electromagnetic radiation through the recombination of e-h pairs across band gap

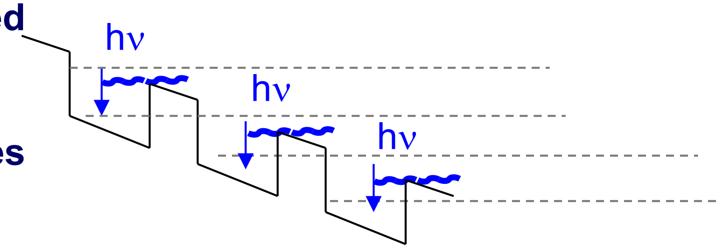


❖ λ → **0.7-0.9 μm, 1.2-1.7 μm, 2-2.4 μm 4- 20 μm**

Alternative:
Development of intersubband quantum cascade lasers



Intersubband transition
- emission is achieved through the use of intersubband transitions
- photon energy depends on layer thickness & can be tailored
- unipolar device
Cascade process
- achieved in a repeated stack of semiconductor superlattices
- each electron emits N photons



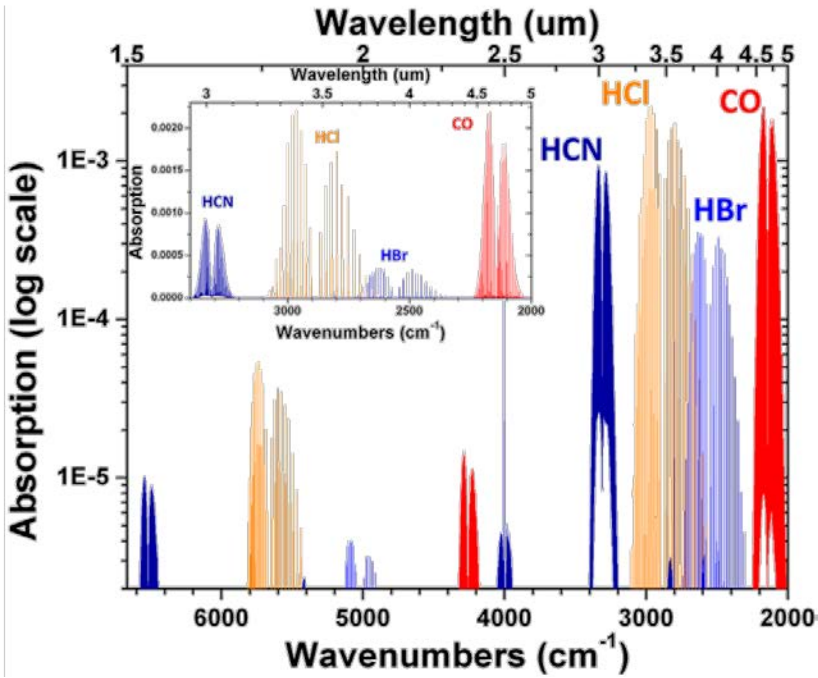
Quantum cascade lasers in the 5-10 μm have been demonstrated recently (very promising)
In the current material system the short wavelength is limited to ~ 4.5 to 5 μm due to the band off-set between InGaAs/InAlAs.

Important Gases for Air Monitoring

- **Fundamental absorption lines in the range 3- 5 micron**

- **Weaker overtones at the shorter wavelength**
  - -Custom lasers Laser available

- **Smaller size sensor/Increased sensitivity can be achieved using the fundamental absorption**
  - -Very limited Laser availability in the 3-5 μm range
  - - Low-power-consumption lasers operating at fundamental absorption wavelengths (3-5 μm) do not exist



- **Availability of efficient lasers in the 3-5 μm range will enabl the possibility of a sensitive, reliable, hand held sensor**

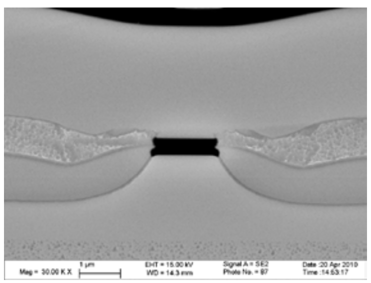
InP- based lasers

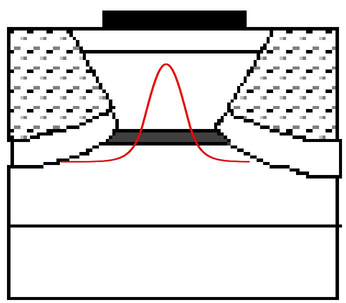
(1.1-2.1 μm range)

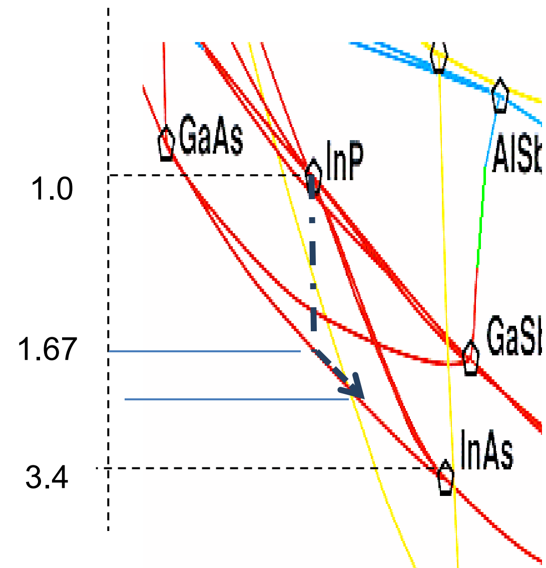
H_2O @ 1.87 μm, CO_2 @ 2.03 μm

InP is the best choice of substrate
Easy to grow high quality expitaxial layers
Fabrication techniques for InP are mature

Single spatial mode by introducing waveguiding In lateral dimension

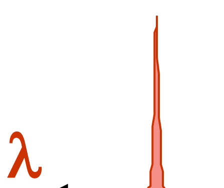


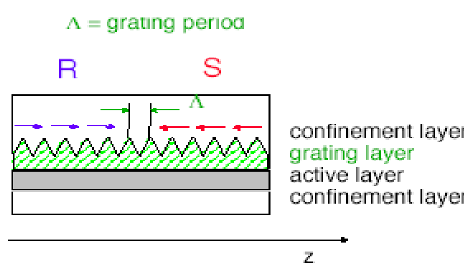




Lattice constant vs.energy bandgap

Single longitudinal mode
Frequency selection is achieved by periodic perturbation along the propagation direction (modulation of the effective index)

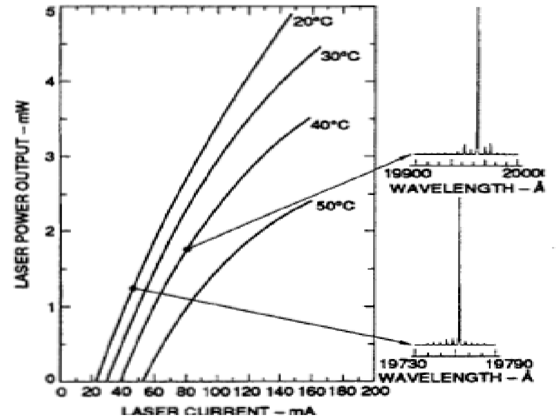




Control

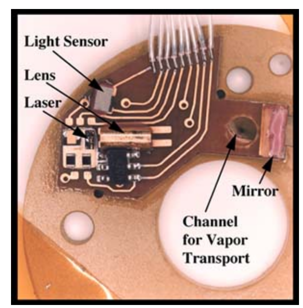
InP- based lasers

Hermetically packaged



Light-current performance

delivered to
Mars 98 mission



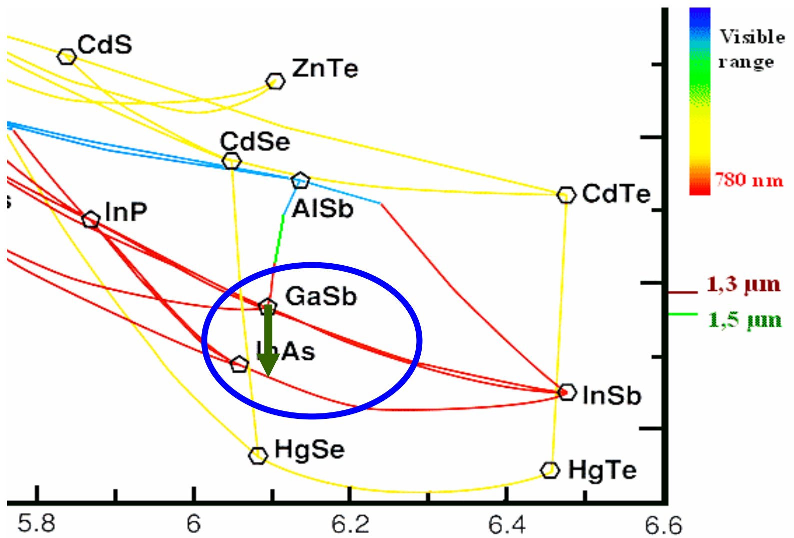
DS-2 TDL
water probe

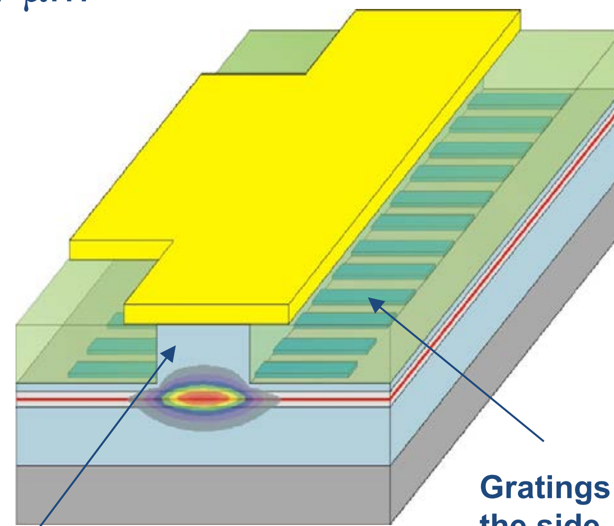
Longest wavelength is limited to ~2.1 μm due to accumulation of strained in the active layer

GaSb type-I lasers

(2-3.7 μm range)

Potential to have lasing in the 2-4 μm
Currently limited to 3.0 μm





Issues concerning the single mode operation of GaSb lasers

- Buried mesa design is not possible
- Epitaxial regrowth over gratings for DFB very not developed

Laterally Coupled Concept

R. D. Martin, S. Forouhar, S. Keo, R. J. Lang, R. G. Hunspreger,
R. Tiberio and P. F. Chapman: IEEE Photon. Tech. Lett. 7 (1995) 244.

Type-I laser at 2.0 micron

Laser Structure	Thick (nm)
GaSb Substrate n-type ~E18	
n-GaSb Buffer	500
n-Graded to Al0.85GaAsSb	200
n-Cladding Al0.85GaAsSb	1500
WG Al0.3GaAsSb	400
QWs In0.23GaSb Strain ~1.45%	**12.5**
Barrier Al0.3GaAsSb	40
QWs In0.23GaSb Strain ~1.45%	**12.5**
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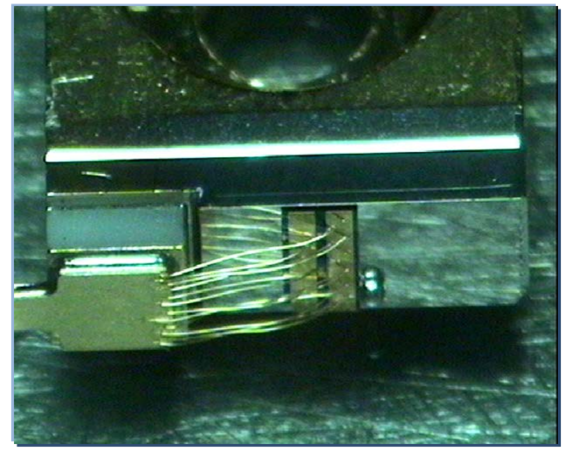
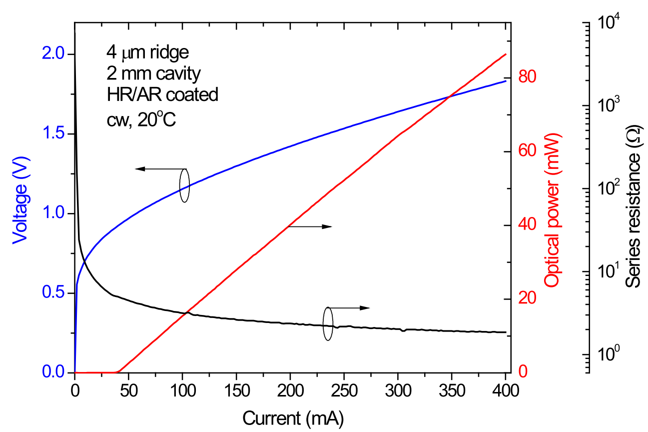
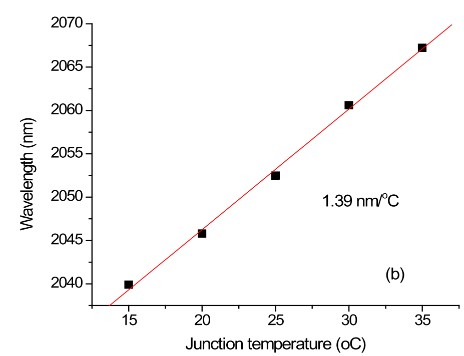
QWs In0.23GaSb Strain ~1.45%	**12.5**
Barrier Al0.3GaAsSb	40
QWs In0.23GaSb Strain ~1.45%	**12.5**
WG Al0.3GaAsSb	400
p-Cladding Al0.85GaAsSb	1500
p-Graded to Al0.1Ga0.9AsSb	200
p-GaSb cap	100





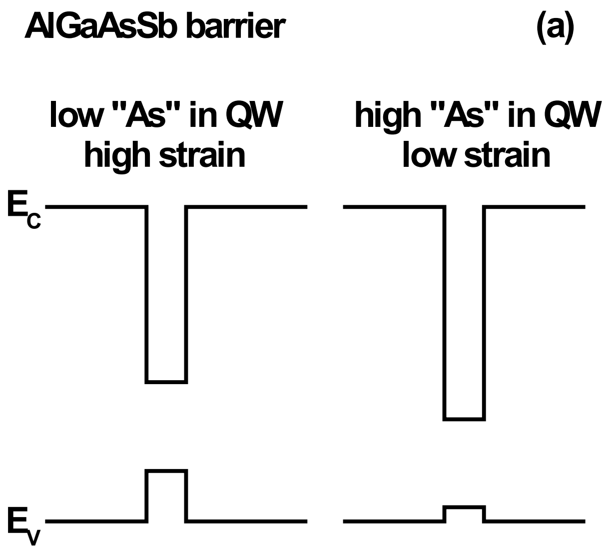


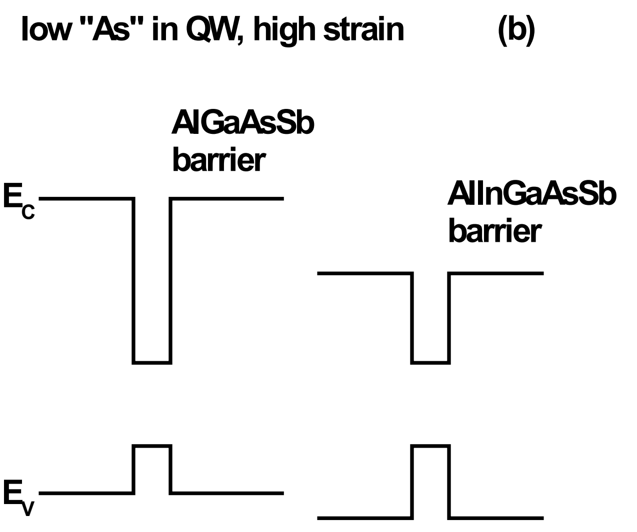
Diode Lasers Operating in 3-3.5 μm

- Laser wavelength is increased above 3 μm by adding more In and As into InAsGaSb QWs.
  3 μm (In 50%, 11 nm) changes to 3.3 μm (In 56 %, 13 nm)

- Use of InAlGaAsSb barrier material alloys improves hole localization

- Quinternary InAlGaAsSb waveguide core



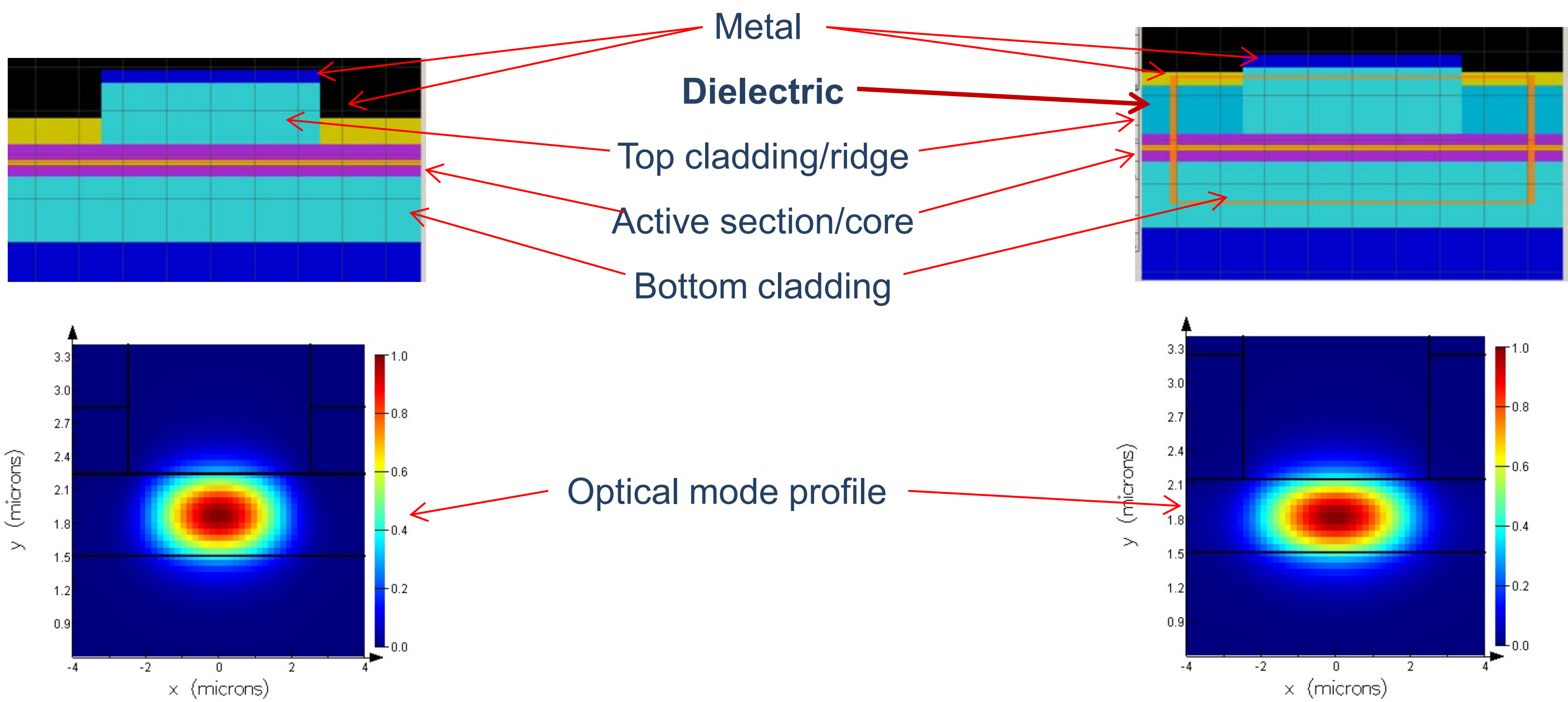


Optical modeling

- **Optical loss due to the optical mode overlap with a metal**
- **Optical loss can be significantly reduced by depositing dielectric layer on the side of the ridge**

5 μm ridge width
Meta directly on Core
Loss 56.8 cm^{-1}

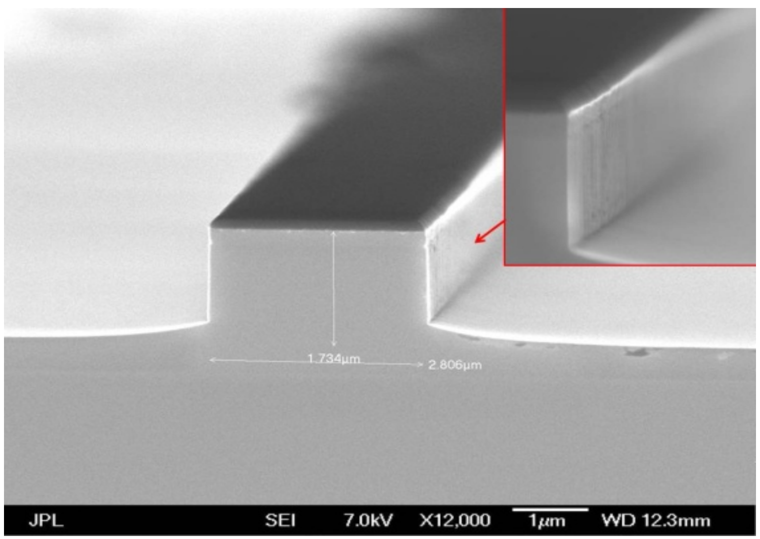
5 μm ridge width
Metal on1.0 micron dielectric
Loss 0.34 cm^{-1}



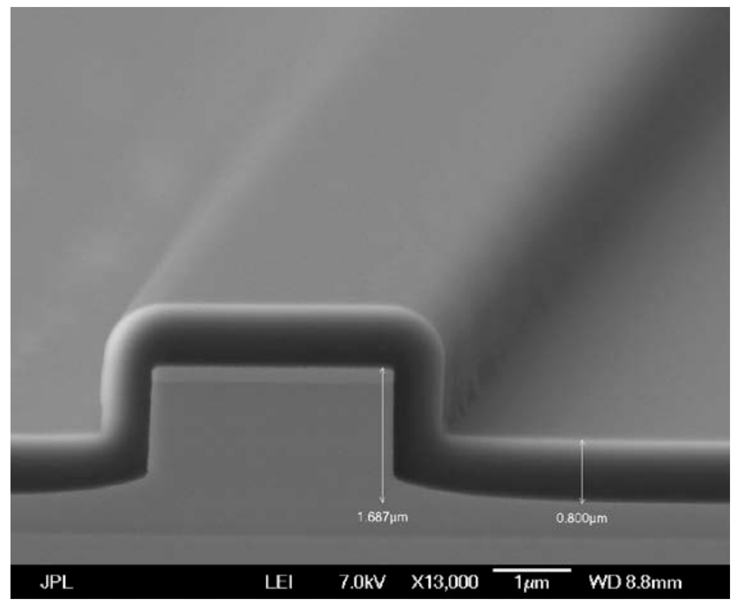
Narrow ridge devices: Fabrication

- Narrow 3- and 5μm ridge waveguide devices were fabricated

- Thick layer of silicon nitride was deposited on the surface in order to lower wavegude optical loss arising from the overlap of the optical mode with top metal contact



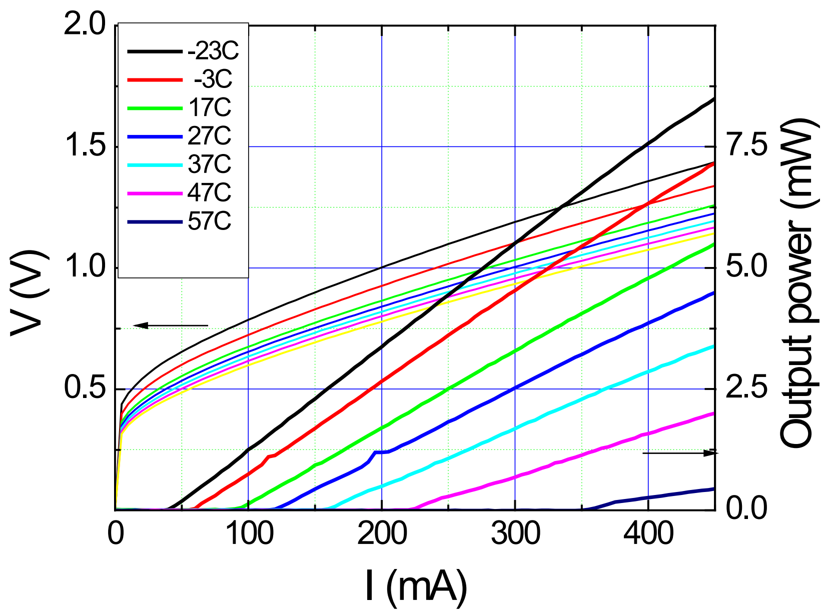
An SEM image of a 3 mm laser ridge with an inset of the sidewall captured at a higher magnification (33,000x)



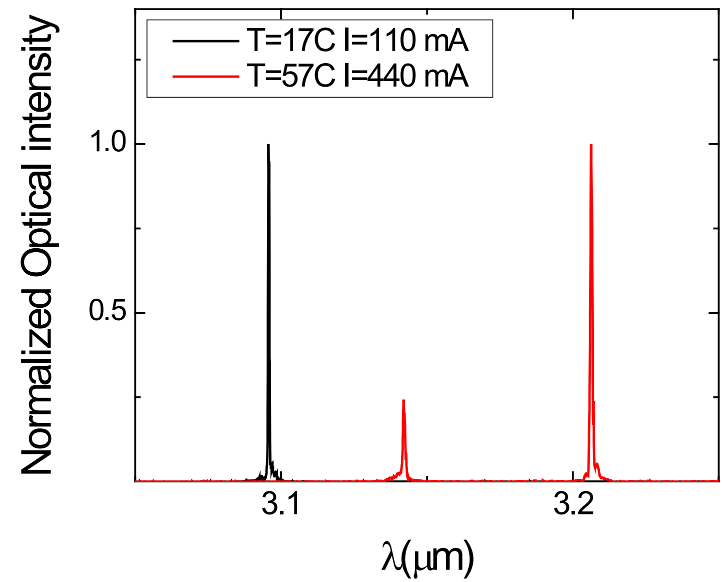
An SEM image of a 3μm laser ridge that has been coated with 8000Å of PECVD silicon nitride

Narrow ridge devices: Performance

Maximal operational temperature of narrow ridge devices was increased from -10 ^{0}C to 57 ^{0}C by depositing thick SiN layer



CW light-current-voltage characteristics of 5-µm-wide 2.5-mm-long ridge waveguide lasers in temperature range from -23 ^{0}C to 57 ^{0}C



Laser spectra of developed mid-IR diode laser operating in CW mode at various temperatures

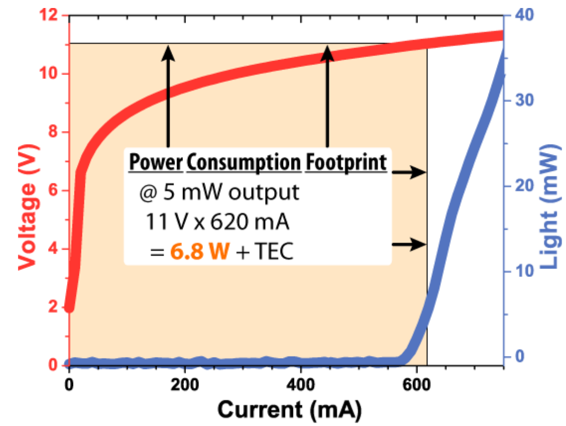
Diode Lasers Operating in 4.0-5.0 µm

Quantum Cascade (QC) lasers are the state-of-the-art mid-infrared (4 – 12 µm) semiconductor light source.

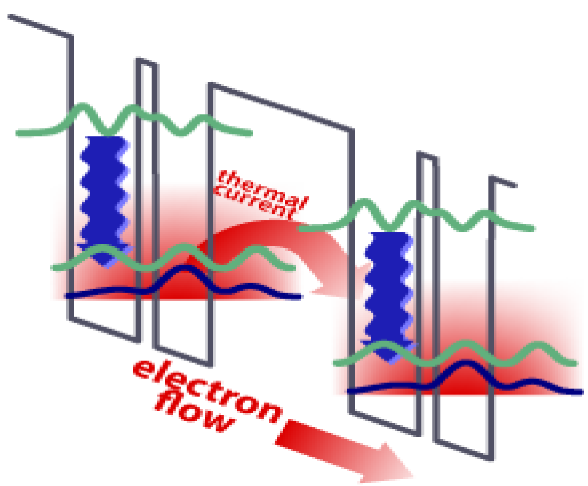
Current state of QC lasers

- High room-temperature (RT) current draw
- Operating voltage typically > 10 V

- **Result: Today's lasers have consumption power requirements that bust power budgets**



- **Our recent data have shown that a parasitic "thermal current" is a primary contribution to high threshold currents at room temperature.**
- **As voltage is applied to the laser, thermally excited electrons "leak" out of the quantum wells.**



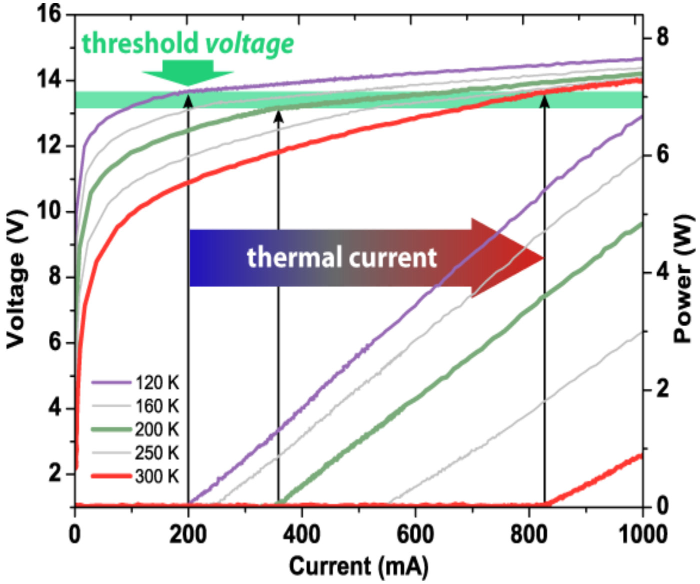
Our Approach

- Our new approach focuses on the requirement of reaching *threshold voltage* rather than *threshold current.* The objective is to reach threshold voltage with minimal current input.

- Current QC lasers achieve substantially better performance at *cryogenic temperatures* due to the *absence of thermal current*. By reducing/eliminating thermal current at room temperature, we will achieve RT performance that approaches cryogenic performance.

- We will develop "trap states" in QC lasers. These trap states will hold electrons and prevent current flow until enough voltage can be applied to reach threshold voltage.

- This design strategy will work best at wavelengths near 4 μm; longer wavelength lasers at 8 μm and beyond may see less benefit.



The above plot of voltage and light output power versus current shows the effect of "thermal current". A temperature-independent threshold voltage is required to turn the laser on. At higher temperatures, the threshold current is greater because of the "thermal current" contribution.

Summary of Part 1

- Significant advances have been made both in performance and reliability of semiconductor lasers

- Low power consumption single frequency lasers at the wavelengths of interest to environmental monitoring are available or will be available in the near future

- The tunable laser spectrometers can provide substantial improvement on size and reliability over the current state of the art instruments for monitoring of major constituents and post fire contaminants