Low power consumption lasers for miniature optical spectrometers for trace gas analysis

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Outline

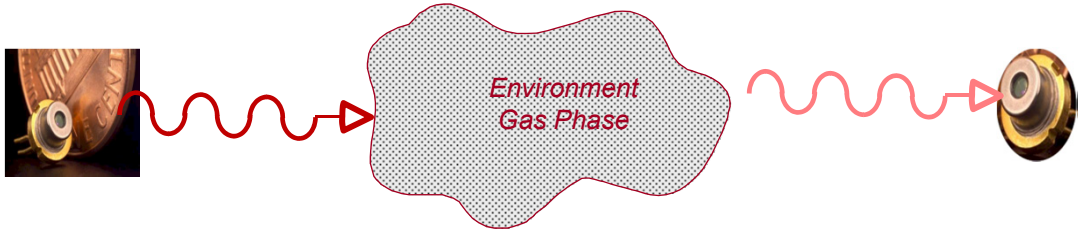
- Introduction
- NASA's interest in laser spectroscopy
  - Earth
  - Planetary
  - Environmental
- Tunable Laser Spectrometer for Mars (TLS)
- Laser spectrometers for manned space mission
- Semiconductor laser status
- Conclusion

Gas Analysis Techniques

Common techniques in use are:

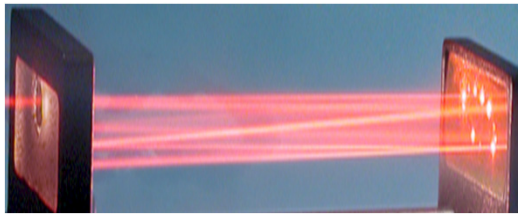
- Electrochemical
- Fourier Transform Infrared Spectroscopy
- Mass spectrometer
- ***Tunable Laser Absorption Spectroscopy***

Direct absorption spectroscopy relies on small change in power of the laser *(limited detectability 10^{-3} range)*



Modulated techniques relies on Wavelength or Frequency modulation spectroscopy *(detectability in the 10^{-5} range)*

Cavity enhancement (detectability in ppm to ppb)



Good features:

- High sensitivity
- High selectivity
- Non-intrusive
- Minimum calibration

NASA's interested in laser spectrometers

Earth and planetary atmospheric studies

-Characterize and understand chemical and dynamical aspects of the earth's atmosphere:

- Understand natural and human effects on stratospheric ozone and the chemical cycles of ozone, both globally and the enhanced loss in polar regions
- Mapping the global distribution of water vapor and water vapor isotopes, in order to understand aspects of Earth's water cycle
- Mapping troposphere ozone and improving our understanding of processes affecting air quality

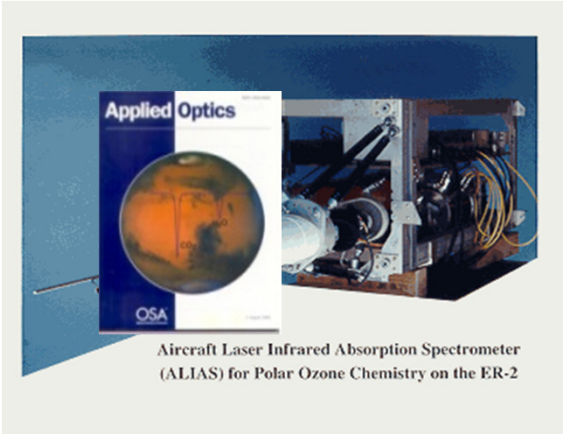
NASA's interested in laser spectrometers

Earth

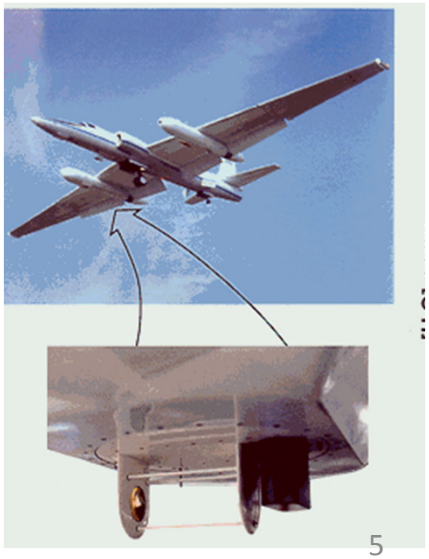
- 6 Balloon & Aircraft Instruments:
  - 500+ aircraft flights (Global Hawk, WB-57F, ER-2, DC-8) in 12 major missions;
  - 20 high-altitude balloon flights
  - First TLS measurements of O3, CO, CO2, CH4, NO2, HCl, HNO3, NO2, NO/ NO2, water isotopes

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

Aircraft Laser Infrared Absorption Spectrometer (ALIAS)



Laser Hygrometer for the ER-2, and WB57F Aircraft

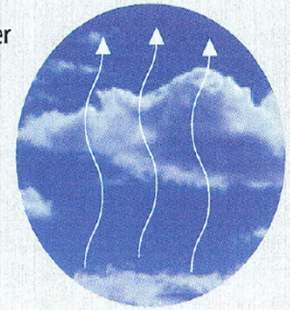


Commercial potential (tech transfer)

Accurate weather forecasting

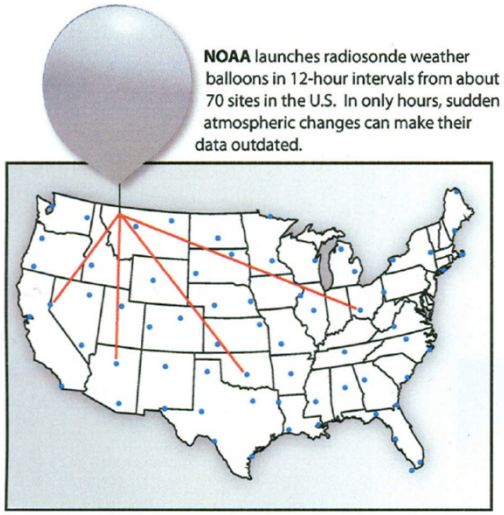
Measurements of water vapor, wind, temperature and pressure at all levels of the atmosphere.

Rising columns of water vapor affect and generate the weather.



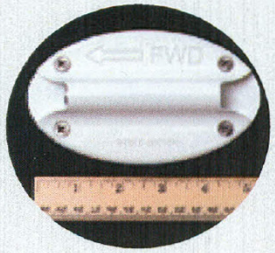
Unpredictable weather costs billions annually in property damages and aviation fuel costs.

Better aviation routing will reduce fuel cost by 5% to 10%.

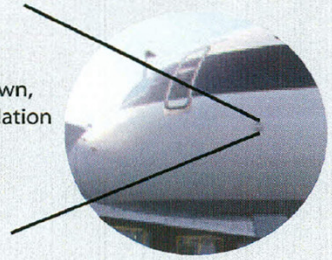


NOAA launches radiosonde weather balloons in 12-hour intervals from about 70 sites in the U.S. In only hours, sudden atmospheric changes can make their data outdated.

A patented air sampling device uses a compact and virtually flush design, proven effective for sample collection.



The air sampler attaches to the fuselage as shown, without degradation of aircraft performance.



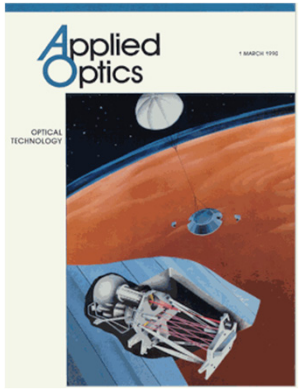
WVSS-Laser based moisture detector. SpectraSensors Inc.

NASA's interested in laser spectrometers

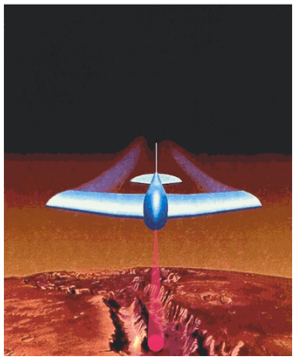
Planetary

Considered for Mars, Titan, Venus, and Europa to measure biogenic gases and their isotopic ratios as signature of life

PIRLS instrument for the Cassini Titan Probe tunable lead-salt diode lasers operating at 82 K, and scanning over typically 2 cm^{-1} at selected, mid-infrared wavelengths (3-5 μm). CH_4, CH_3D, $^{13}CH_4$, C_2H_6, and C_2H_2; the nitriles HCN,
1990



MIRLS instrument for Mars photochemistry developed for lander and Mars Airplane applicationsTo search for and identify local sources of biogenic and geochemical activity from near-surface measurement of atmospheric gases such as CH_4, N_2O, OCS, and CO, and to search for local sources of H_2O
1996-1998

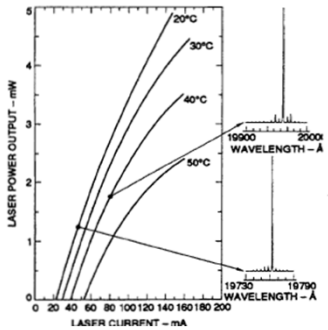


Mars Volatiles and Climate Surveyor (MVACS)

Planetary

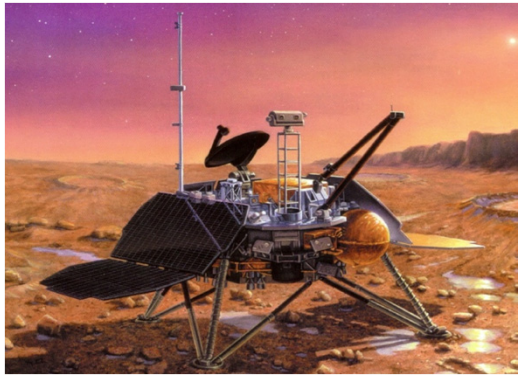
Tunable Diode Lasers (TDL) to measure water vapor amounts and specific isotopes of water and carbon dioxide at 2.0 micron

Hermetically packaged



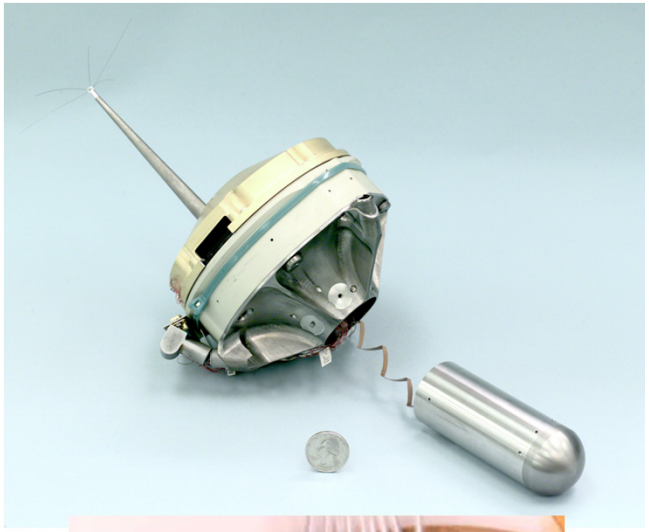
Light-current performance

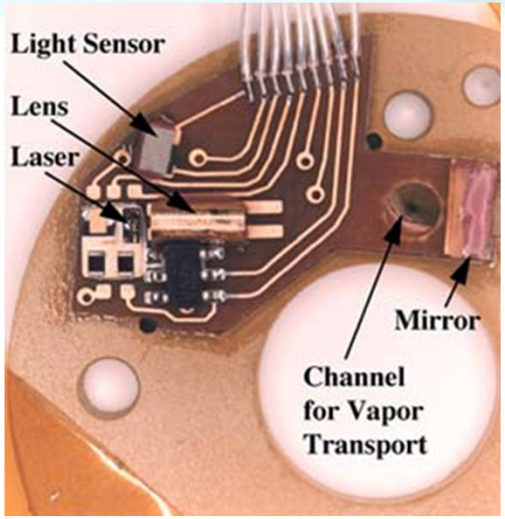
Herriott Cell configuration



Schematic of the failed Mars 98 lander

DS-2 TDL water probe

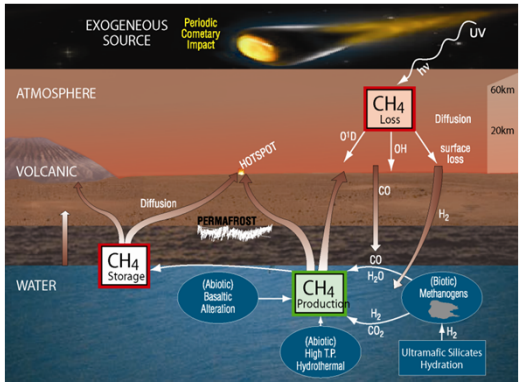


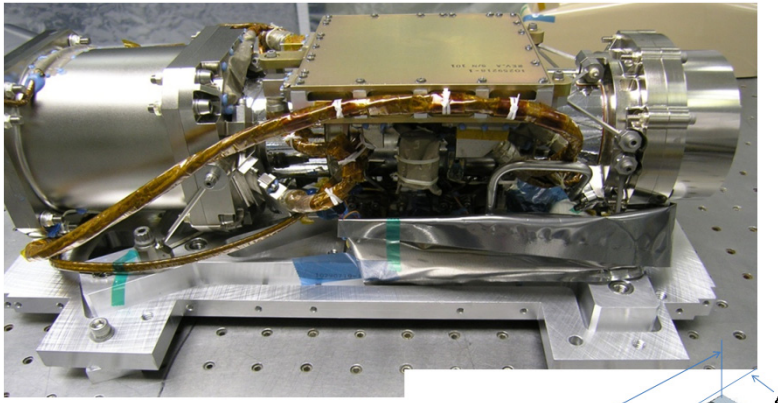


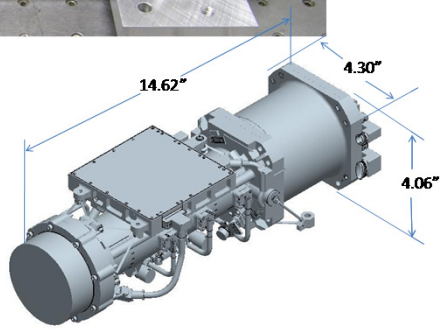
Tunable Laser spectrometer for Mars

Oct. 2011 launch

methane in atmosphere of Mars

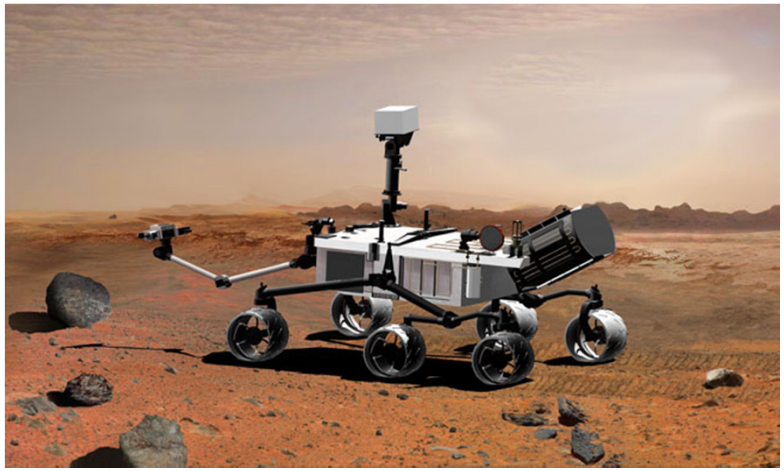




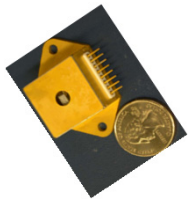


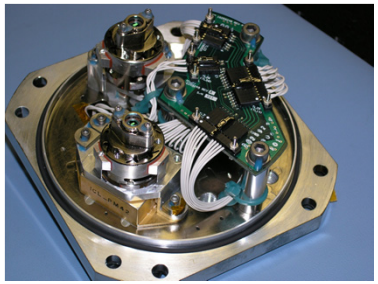
Detects methane, water, and CO2
Total Mass = 4.5 kg.
Power = 25 W 16.7 W average

Mars Science Laboratory (MSL) rover



Two laser system 3.27 μm and 2.78 μm

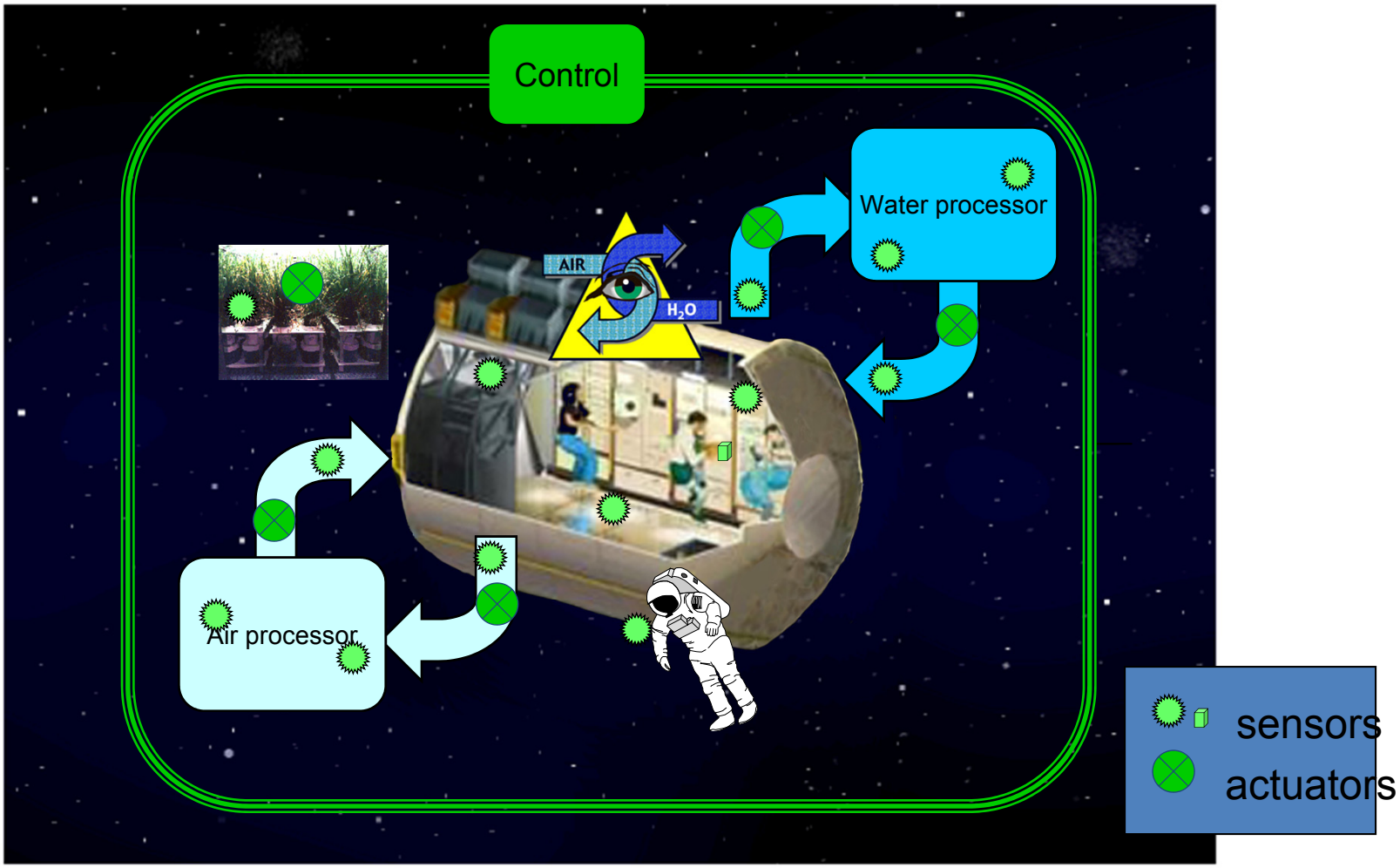




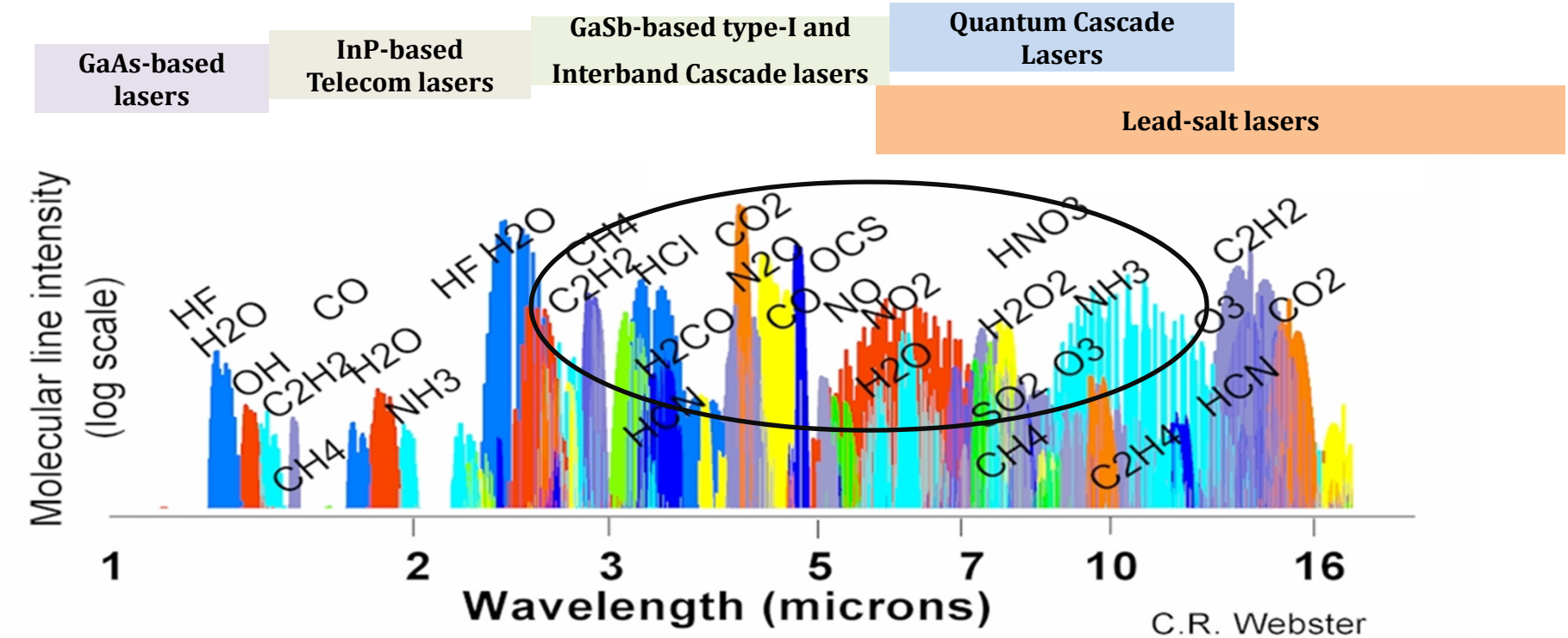
NASA's interested in laser spectrometers

Environmental monitoring

- Real time measurement, fast response, reliable
- Hazardous event detection
- Monitoring event, when is safe to breath again



Laser Diode Wavelength Range

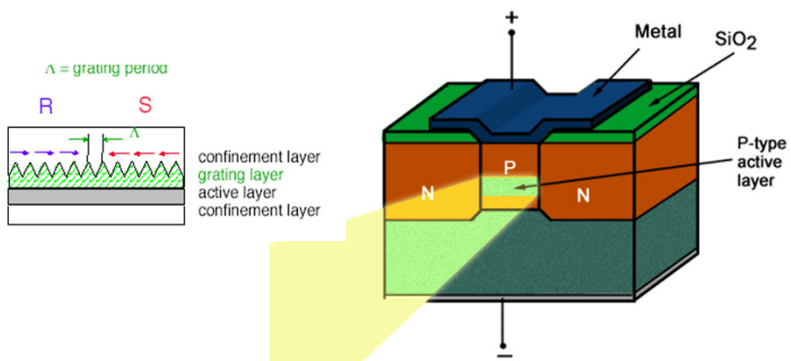


- Fundamental absorption of gases are in the 3-10 micron
- No single laser can cover the entire wavelength of interest
- Not all laser types perform the same nor have the same reliability and life expecta
- Variety of material systems, designs, and fabrication techniques need to be developed for diode lasers to cover the wavelengths of interest

Laser: Requirements and Types

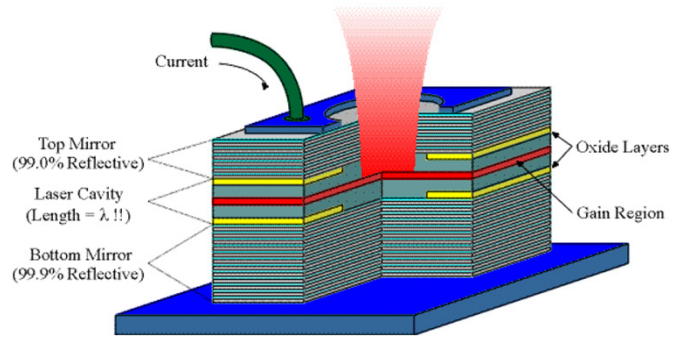
Requirements
- Wavelength coincide with the absorption of the gas of interest
- Narrow spectrum
- Wavelength tunable
- Reliable

Edge emitters



- Requires either integrated or external grating for single frequency
- Wavelength from 760 nm 3000 nm for type-I
- Drive power <300 mW
- Wavelength from 3.0-10 μm for IC and QC lasers
- Drive power in the watts
- Beam quality (elliptical)
- Output power tens to 100s of milliwatt

VCSELs



- Inherently single frequency
- Wavelength from 760 nm 2300 nm
- Low drive power <100 mW
- High beam quality (circular)
- Type-I laser structure
- Low output power < 5 mW
- Only demonstrated in type-I design which limits the wavelength range
- Multi stack reflector will be a limiting factor at longer wavelength

Tunable Laser Spectrometer (TLS) on the 2011 Mars Science Laboratory (MSL) Mission

Goal:

- measure biogenic gases and their isotopic ratios as signature of life

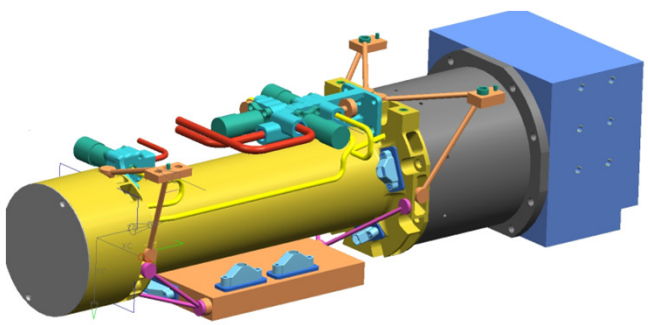
Requirements:

- TLS shall measure targeted gases that originate from (i) the Mars atmosphere; (ii) adsorbed to soil; or (iii) bound to rocks and released in pyrolysis. Specific target gases are H_2O, CH_4, N_2O, CO_2 and H_2O_2.

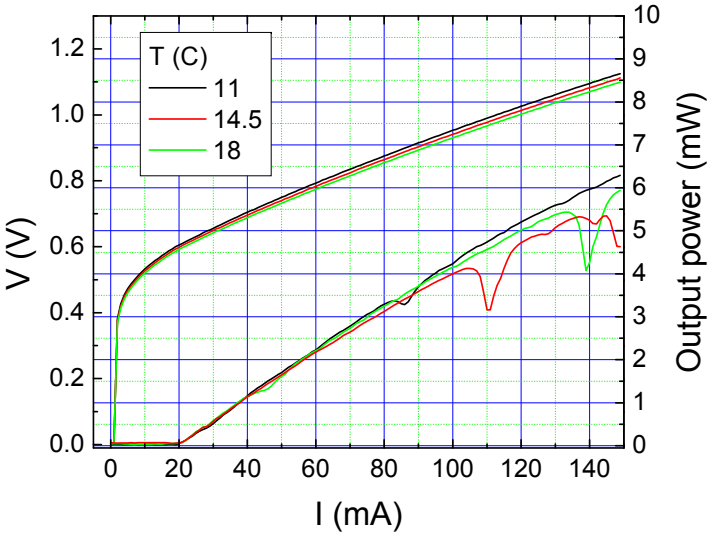
TLS original design:

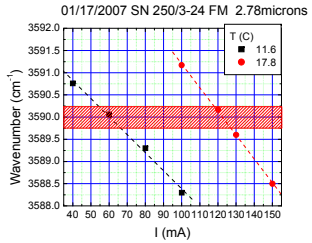
- 2 near-IR TDL's from Nanoplus, 1 IC laser developed by JPL, and 1 QC laser from Alpes

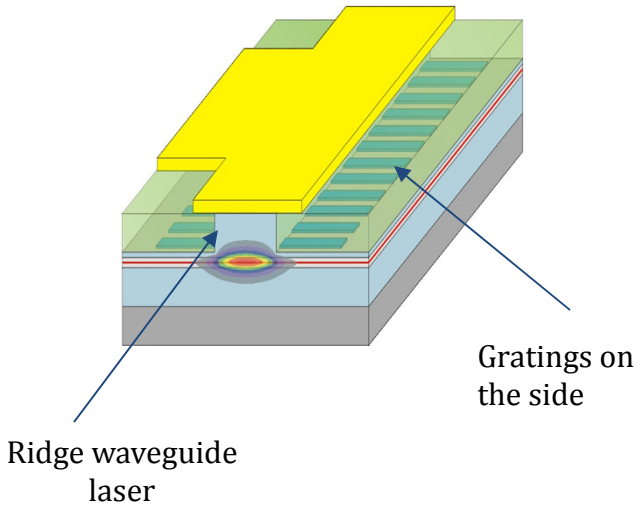
Gas	Wave-length (μm)	Direct Atmosphere	With pre-concentration
		Limit of Detection	
H_2O	2.64	1 ppmv	10 ppbv
CH_4	3.27	1 ppbv	10 pptv
CO_2	2.78	0.5 ppmv	N/A
N_2O	7.8	5 ppbv	< 5ppbv
H_2O_2	7.8	2 ppbv	< 2ppbv

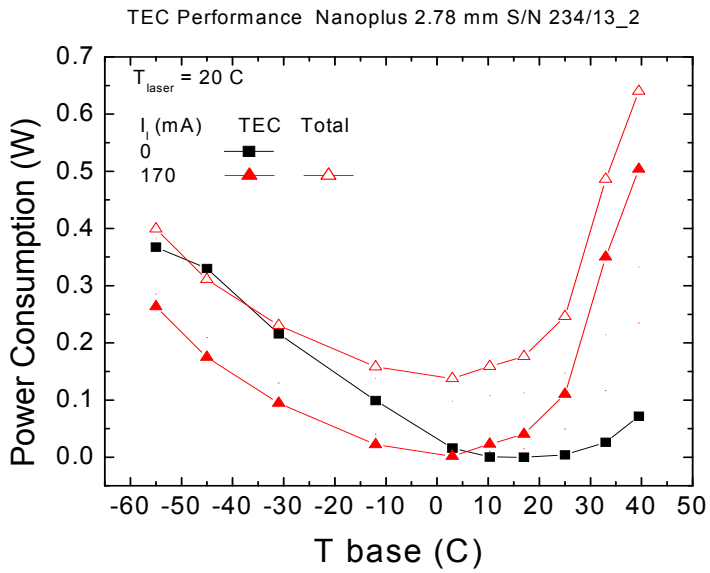


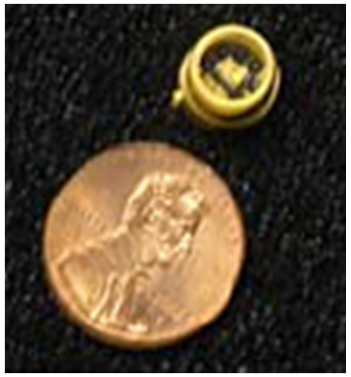
Type-I InGaAsSb LCDFB @ 2780 nm







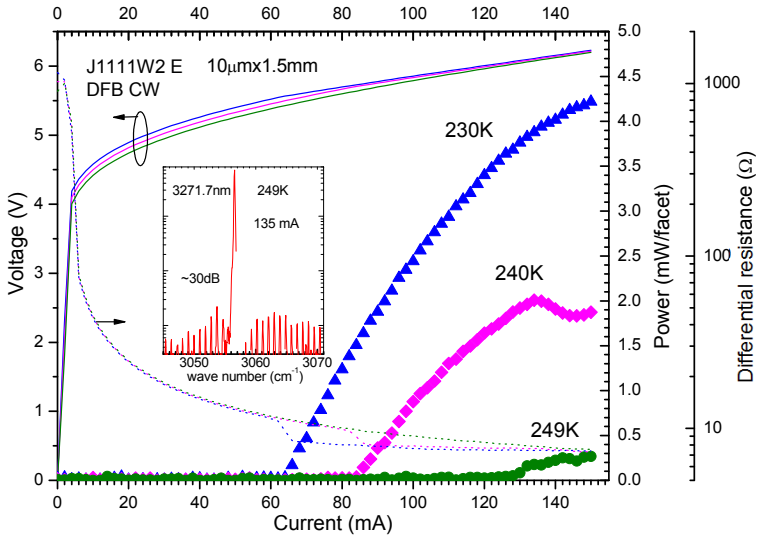


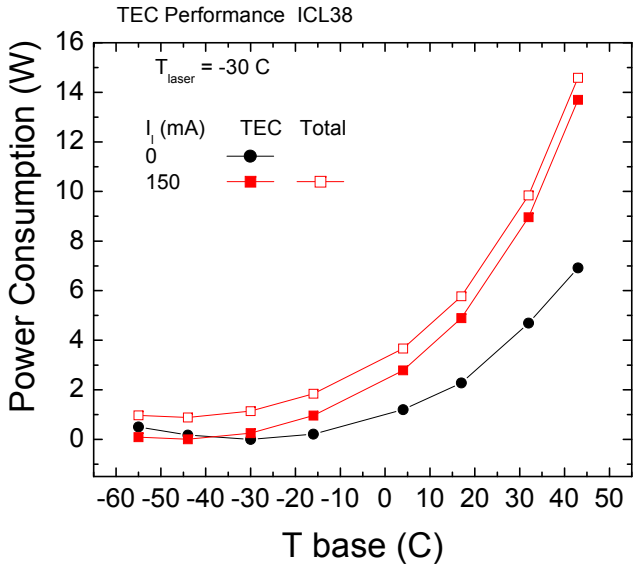


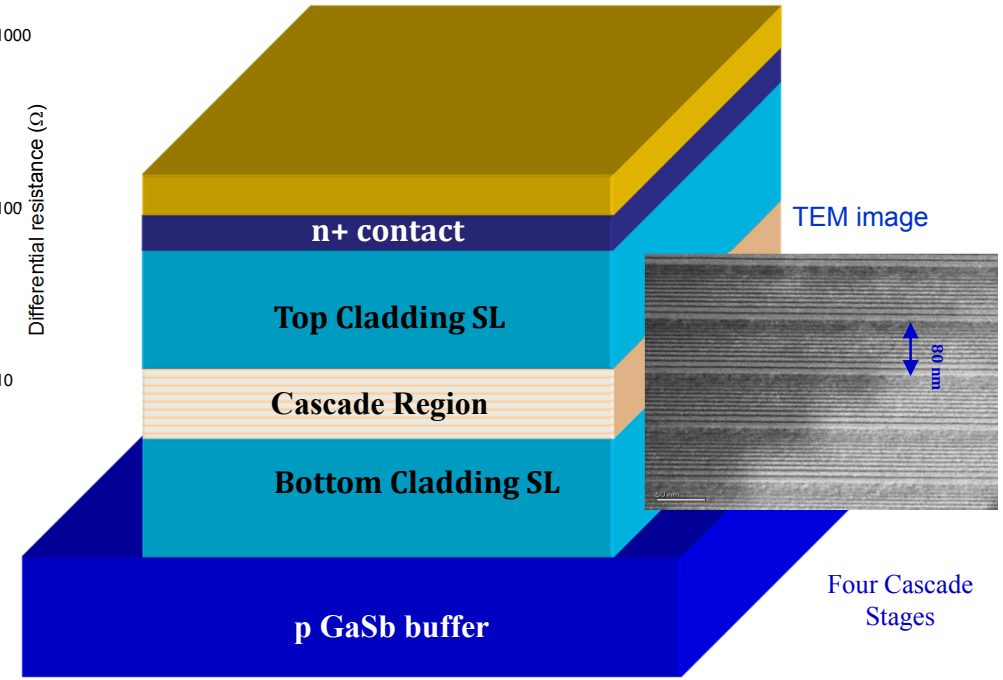
Nanosystems and Technologies GmbH
nanoplus

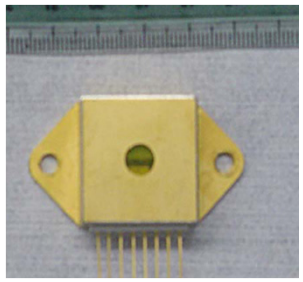
Type-II interband Cascade DFB @ 3270 nm

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





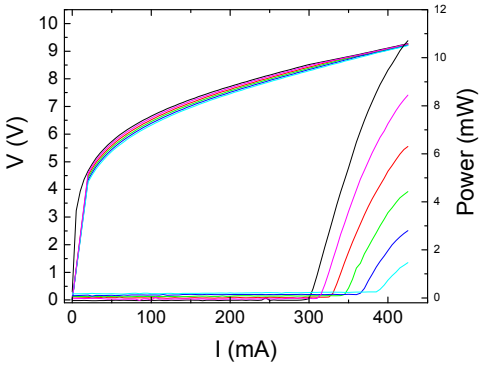


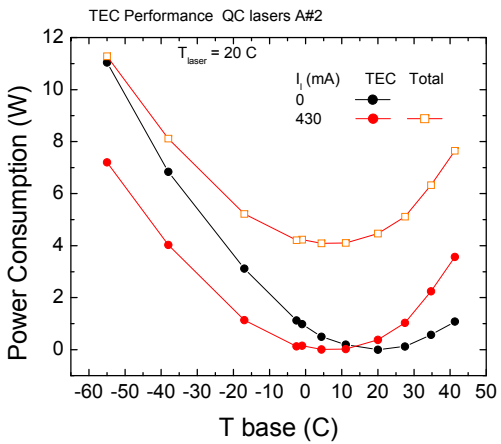


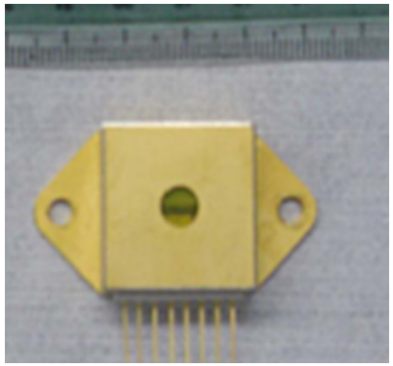
Packaged IC laser with stack of two TECs

Quantum Cascade DFB @ 7800 nm

Alpes Lasers

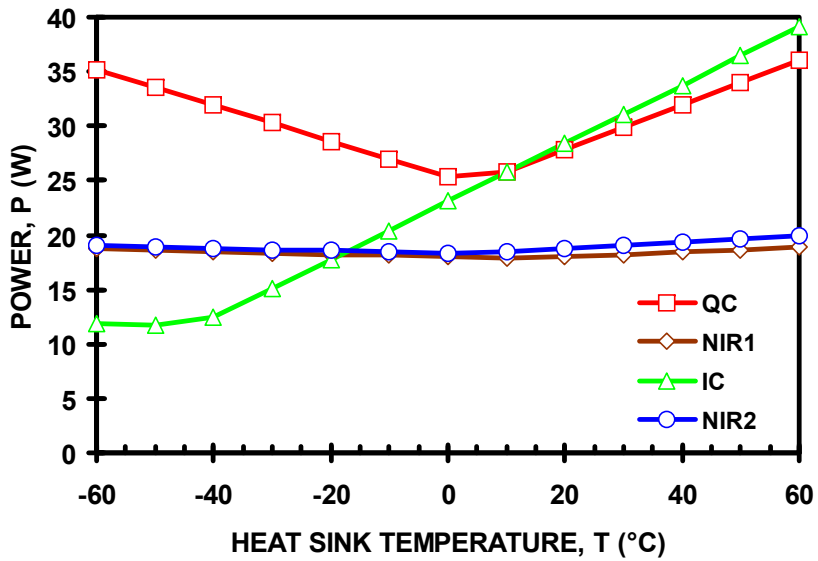






Packaged QC laser with one TEC

TEC Power requirement for each channel in a 4 channel system



File: TLS_Power_6B17.xls

When operated with one laser , TLS power is less than 60 W for heat-sink temps between -60 and +60 °C.
When four lasers are on TLS power is less than 60 W for heat-sink temps limited to -50 and 5 °C.

- Considering mission life time, and operation scenario
- Instruments operation scenario

Lasers power requirement limited the operation of TLS to two lasers

Environmental Monitoring in space

Major constituent measurement

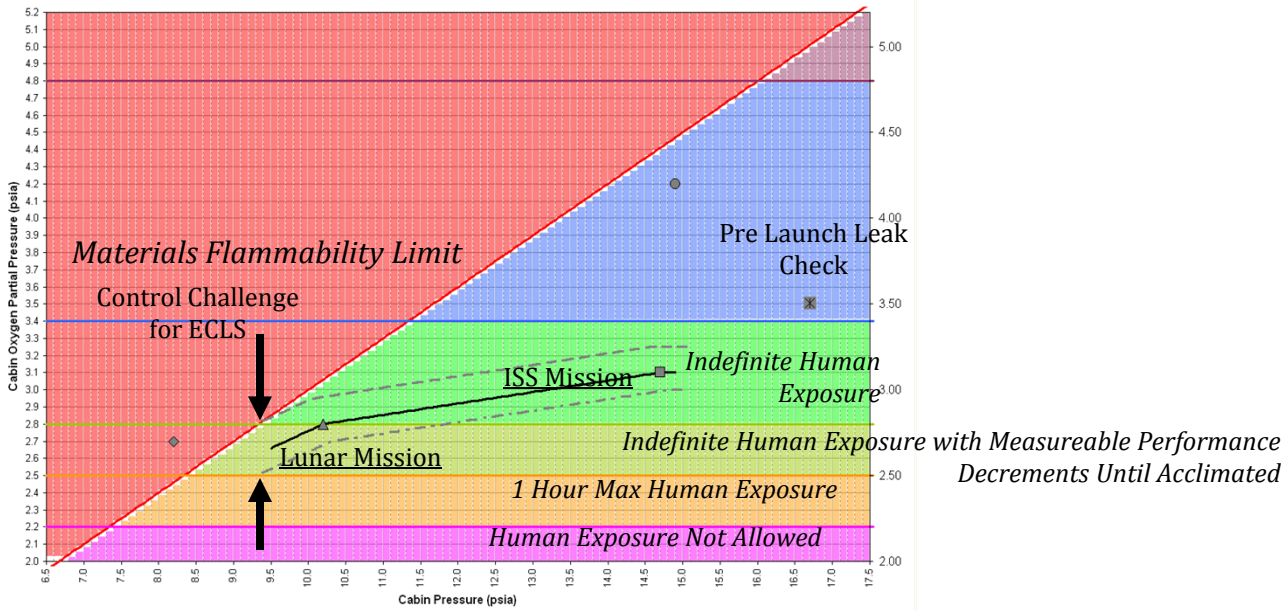
- Continuous monitoring of O2, CO2, N2, H2O

Fire Detection and Suppression System (FDS)

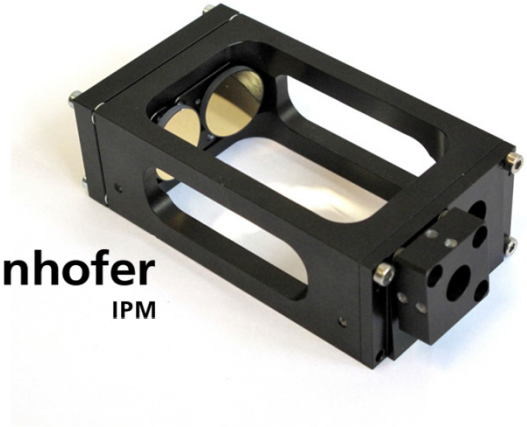
- The FDS includes the vehicle hardware, portable equipment, and M&P processes that prevent, detect, and suppress a fire.

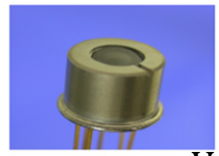
Air Quality Emergency Response System

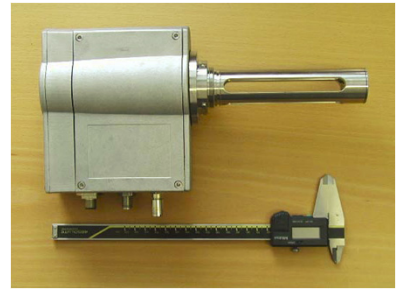
- The air quality emergency response system is the set of portable equipment used to control all unplanned upsets that contaminate cabin air including: fire, ammonia leak, over-temperature event, chemical release, and hydrazine spill.



Environmental Monitoring in space
Combustion products monitor

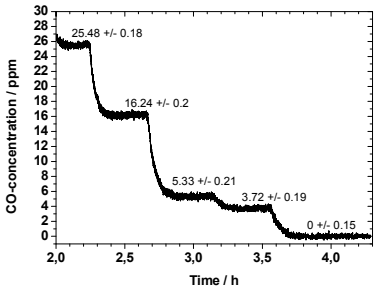


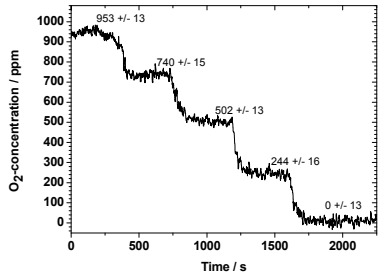




Vaisala's oxygen transmitter, consisting of the spectrometer probe and associated electronics.

- Current status: one cell per compound
- Dimensions of the cell: 12 cm x 6 cm x 3.5 cm (252 cm^3)
- Weigth per cell: 250 g
- Optical pathlength: 2.18 m
- Vertical-Cavity Surface-Emitting Laser (total power consumption: ~250 mW)





Molecule	Wavelength µm	Line strength cm/molecule	NEC 3 σ
O2	0.7648	8.364 E-24	48 ppm
CO	2.362	2.719 E-21	600 ppb
HCl	1.742	1.16 E-20	141 ppb

Availability of efficient lasers in the 3-5 mm range will enable the possibility of a sensitive, reliable, hand held sensor

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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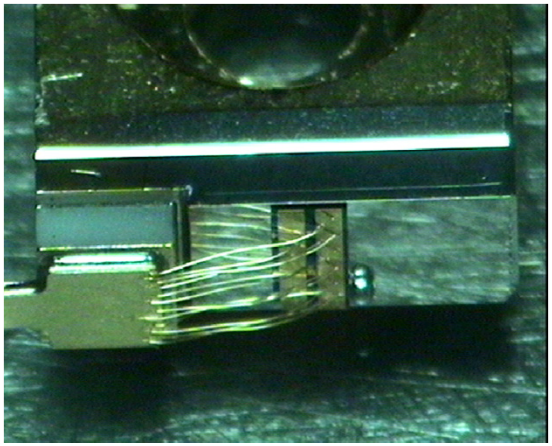
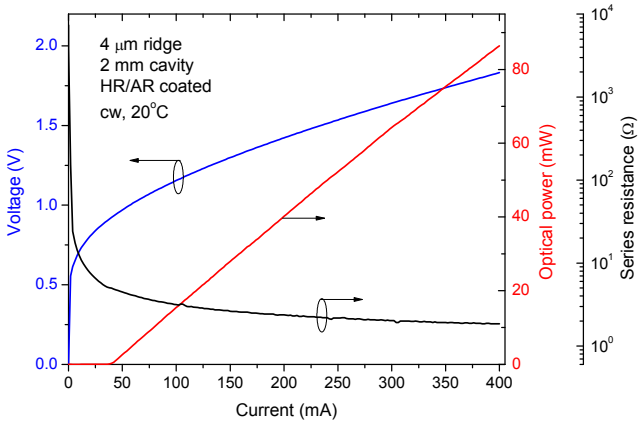
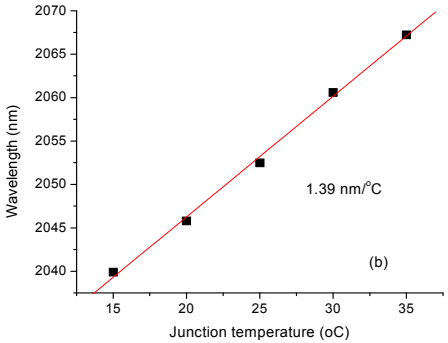
Barrier Al0.3GaAsSb	40
QWs In0.23GaSb Strain ~1.45%	**12.5**
WG Al0.3GaAsSb	400
p-Cladding Al0.85GaAsSb	1500
p-Graded to Al0.1Ga0.9AsSb	200
p-GaSb cap	100





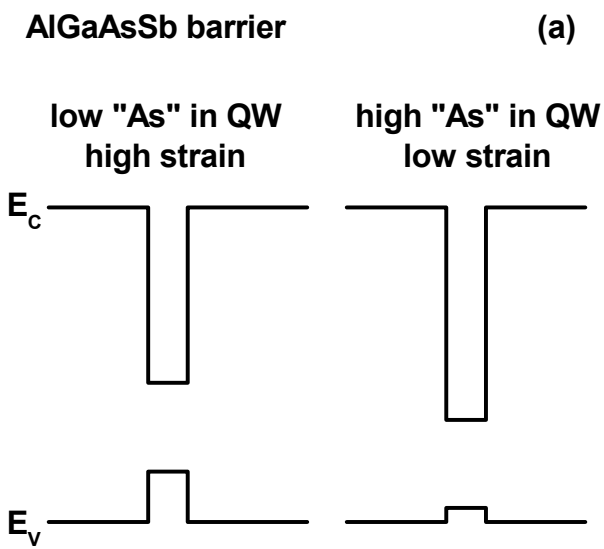


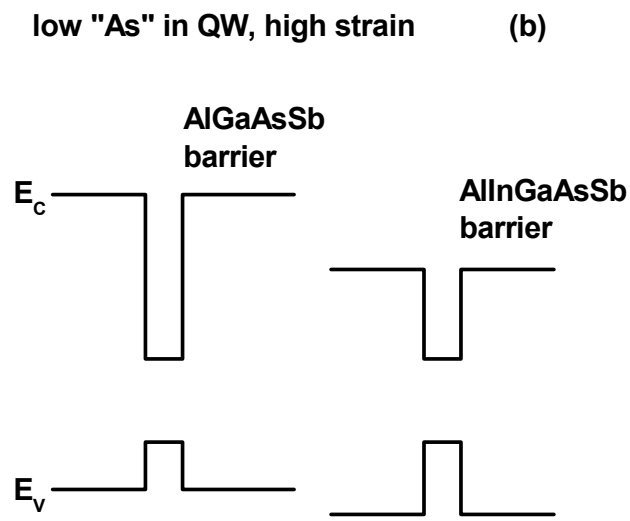
Diode Lasers Operating in 3-3.5 µm

- 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

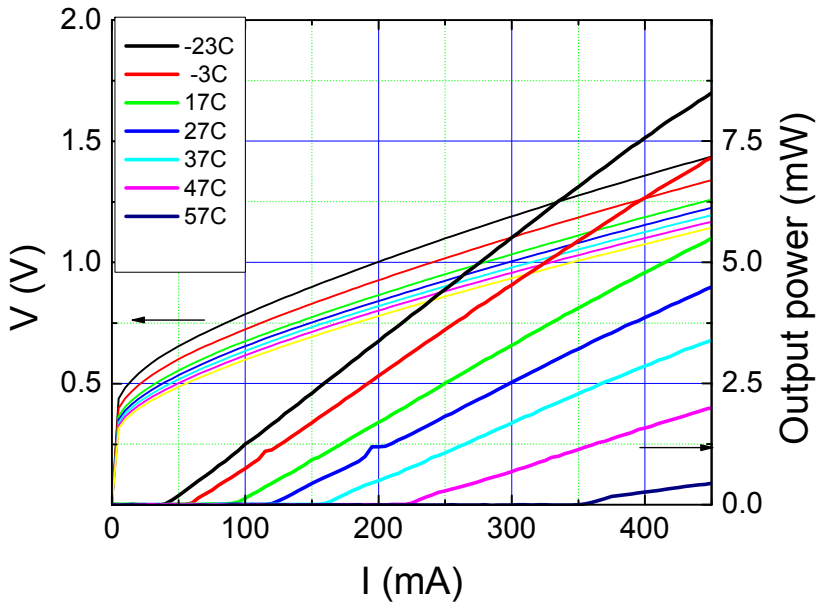
- Quinternary InAlGaAsSb waveguide core



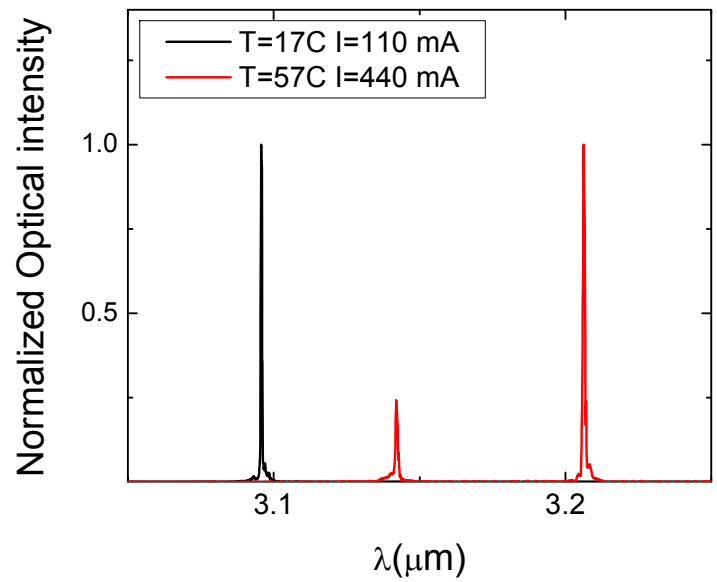


Narrow ridge devices: Performance

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



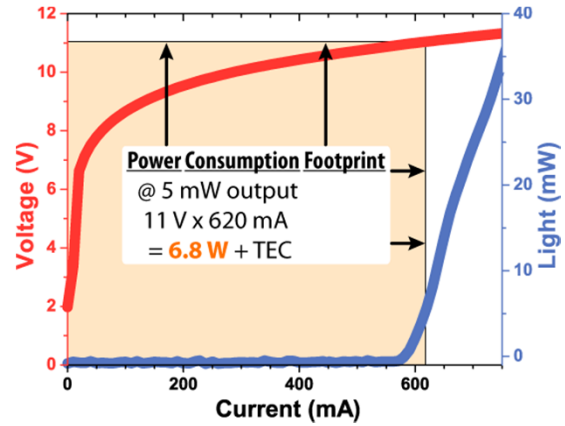
Laser spectra of developed mid-IR diode laser operating in CW mode at various temperatures

Lasers Operating in 4.0-5.0 µm

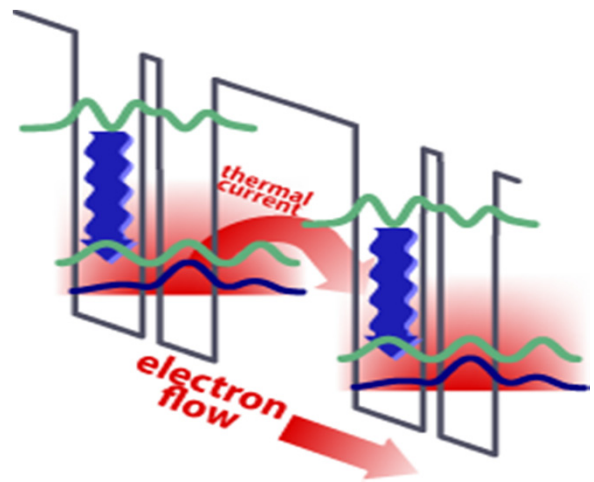
Quantum Cascade (QC) lasers are the state-of-the-art mid-infrared (4 – 12 µm) semiconductor light source.

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.



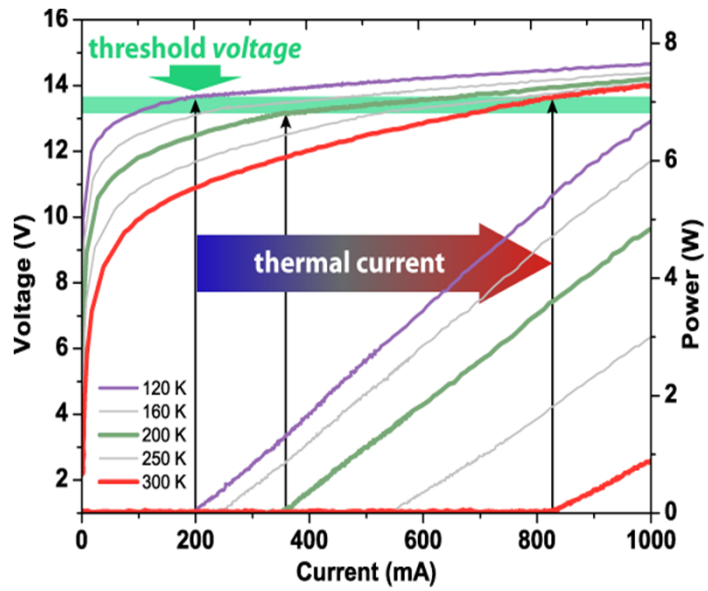
Our Approach

- 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.

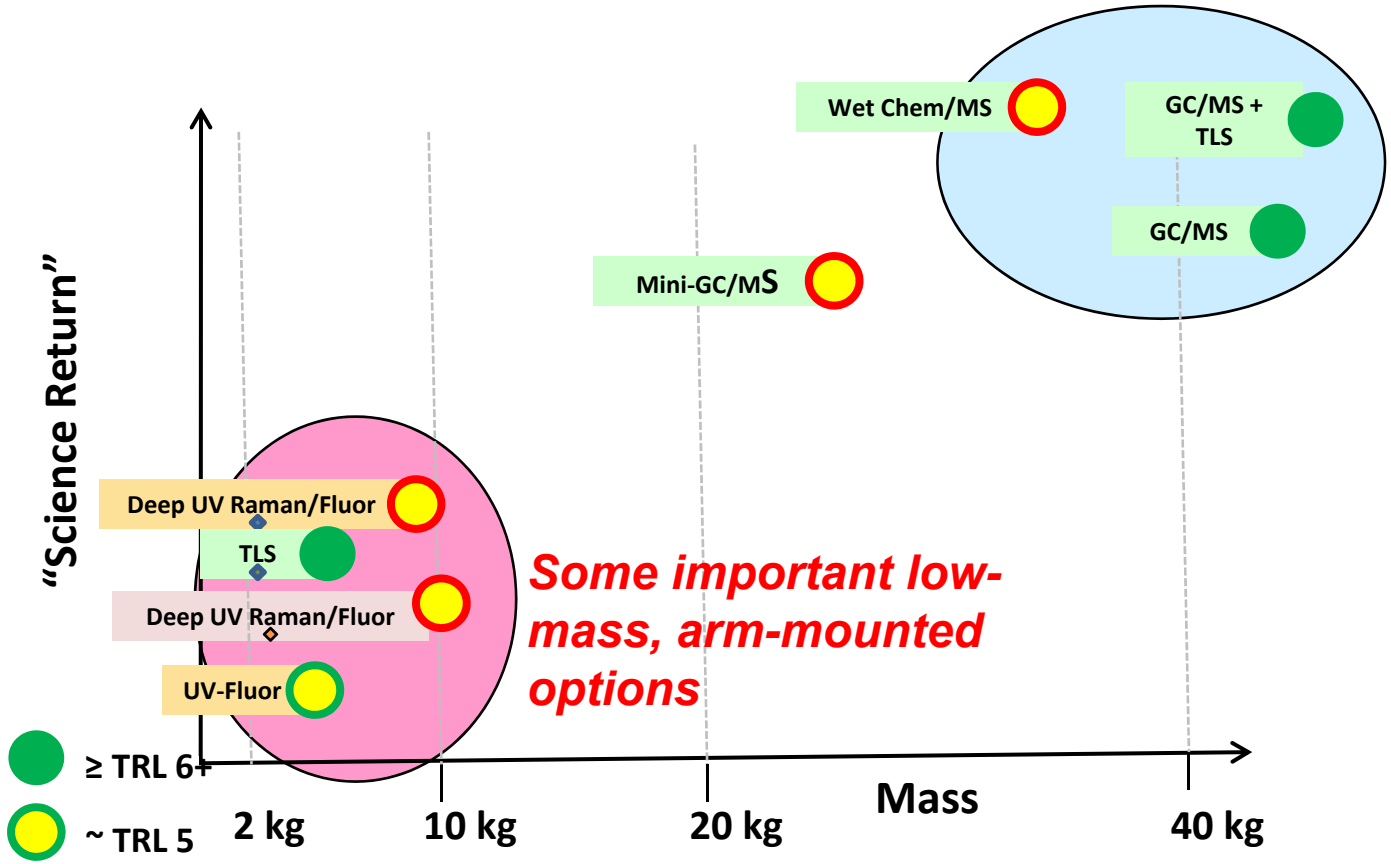
- This design strategy will work best at wavelengths near 4 µm; longer wavelength lasers at 8 µm and beyond may see less benefit.



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

The tunable laser spectrometers are considered as one of the powerful in situ instruments for space



Thank you